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Inge Maria van den Bijgaart

geboren op 8 juni 1988 te Eindhoven

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Maandag 28 augustus 2006 zal het geweest zijn, mijn eerste college aan de Universiteit van Tilburg. Al zou je ook kunnen stellen dat mijn tijd in Tilburg 2 weken eerder begon, met een TIK-week waarvan 'pompen of verzuipen' de beste omschrijving was: veel regen en veel bier. Woensdag 31 augustus 2016 wordt de laatste dag van mijn PhD contract aan de Universiteit van Tilburg. Al vertrek ik eigenlijk al een dag of 10 daarvoor, wanneer Stephan en ik op het vliegtuig naar Göteborg stappen. Tien jaar Tilburg, tien jaar waarin de stad, en misschien zelfs nog meer de universiteit, mijn thuis waren. Ik heb de afgelopen tien jaar geweldig veel mooie mensen leren kennen. Mensen die ik dankbaar ben voor hun gezelschap, hun steun, en voor wat ik van ze heb mogen leren. Te veel mensen om allemaal uitgebreid te noemen in dit dankwoord. Maar laat ik eens een bescheiden poging wagen.

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Hola. Como estas? Je zou verwachten dat, na 4 jaar een kantoor gedeeld te hebben met een Colombiaan, mijn Spaans wat verder zou reiken. Ok dan: salsa tequila corazon cerveza muy bieno =). Dit is gelukkig geen teken van wederzijdse onverschilligheid. Mauricio, je bent de afgelopen jaren mijn maatje geworden, mijn sparring partner/vraagbaak op kantoor en blijde afnemer (en reinforcer) van een neverending supply of baked goods. Het zal even wennen zijn na de zomer, maar we hebben gelukkig nog een project op de rol, en Stephan en ik zullen zeer zeker een keertje in Bogotá komen crashen.

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Inge van den Bijgaart
Tilburg, juli 2016

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Chapter 1

INTRODUCTION

The emission of carbon dioxide (CO_2) and other greenhouse gases contribute to climate change, whose effects and costs may be both unprecedented and unforeseen. To combat these emissions, and the negative environmental externality they generate, policies are required. However, in the complex and dynamic world we live in, the appropriate policies to deal with such an externality are not immediate, and thus the subject of a rich academic, and also political, debate.

If the production of a certain good generates a negative externality, the standard policy recommendation is to levy a Pigouvian tax on such a good.[1] In the context of CO_2 emissions, this would amount to introducing a tax on the emission of CO_2, equal to the present value cost of these emissions (the social cost of carbon, or SCC). With such a tax (or equivalent subsidy or permit price), emitters of CO_2 are forced to internalize the societal cost of CO_2, and efficient emission levels would be chosen.

This policy approach, however, may be suboptimal when we consider additional market failures, or when there exist restrictions on the type or scope of policy instruments available to the policymaker. In such cases, the social cost of the externality will no longer be the sole determinant of the level of the corrective tax, and a tradeoff will need to be made between correcting the externality and other economic concerns.

For instance, think of the world economy, and suppose that only a subset of countries introduce a carbon tax. In response to the tax, carbon-intensive sectors move to the other countries, undermining the effectiveness of the tax to begin with. In this context, Hoel (1996) argues that setting a tax below the Pigouvian level is optimal, and additional policy measures, such as trade tariffs, may be required. Similarly, it has been well-established that the interaction of environmental and innovation mar-

[1] This tax is named after Arthur Pigou (1877-1959) who was the first to propose it.

ket failures may warrant the use of both emission taxes and innovation subsidies Acemoglu et al. (2012); Gerlagh et al. (2009); Jaffe et al. (2005). Then, when emission taxes are not available, additional innovation subsidies targeting 'green' innovation may be justified. Similarly, when innovation subsidies cannot be employed, increasing emission taxes beyond the Pigovian level may be efficient based on the argument that innovation in emission-reducing technologies is suboptimally low otherwise. Finally, the adoption of emission-reducing technologies may require investment in new machinery by firms. A higher emission tax then incentivizes more firms to invest. Simultaneously however, such taxes may erode firm profits, which, if access to credit is limited, reduces their investment abilities. Thus, a balance needs to be sought, between incentivizing and enabling firms to invest.

In the presence of these, and other potential policy tradeoffs, one message prevails: to determine the optimal environmental policy, and set the correct incentives, a thorough analysis of interacting market failures and second-best situations is required. Chapters 2 through 4 deliver such an analysis; Chapter 3 specifically explores the last example, where firms face credit constraints.

Prior to considering deviating from the Pigouvian tax, an assessment of the size of the environmental externality, and thus the amount of the Pigouvian tax, is warranted. For CO_2 emissions this implies determining the value of the social cost of carbon described above. In the environmental economics literature, this SCC is typically determined within large-scale models of the climate and economy. In Chapter 5 I propose an alternative approach and derive and evaluate a simple formula for the social cost of carbon.

Finally, a policy that works in theory may not be as effective in practice. Firms and consumers may be reluctant to adopt new technologies, other than can be explained by a simple cost-benefit analyses, or may be more sensitive to a tax than an equivalent subsidy (or vice versa). In addition, policy may have unintended and unanticipated consequences. The subsidization of biofuels for example has lead to deforestation of rainforests, and the observed shift away from petrol vehicles to more fuel-efficient diesel vehicles has come at the cost of an increase in local air pollution. Even if some of these indirect policy effects are anticipated, their size may be hard to determine ex ante. Effective policymaking thus requires an ex post policy evaluation. In this spirit, Chapter 6 evaluates the the effect vehicle taxes on the average CO_2 emissions from new cars in the EU.

Under the overarching theme of environmental or climate policy, this dissertation comprises several subthemes, which are relevant to two or more chapters. The dominant subtheme is economic dynamics, more specifically, the transition of the current economy to one that is less intensive in CO_2. When one considers climate change, it is not so much emissions today, but rather the entire path of emissions, past, present and future, that determines the extent of climate change. The transition of the economy away from CO_2-intensive production and consumption is required for a sustainable future, and to a certain extent, already taking place. This transition is integral to Chapters 2 through 4; in Chapter 6 I use the already observed shift away from CO_2-intensive vehicles to identify the effect of EU vehicle taxes.

A second subtheme is bounded rationality, more specifically myopia. A rapidly expanding literature in behavioral economics has documented how consumer preferences and rationality deviate from the neoclassical assumptions. The use of assumptions accounting for these behavioral deviations is becoming more common in economic models, which, also in the field of environmental economics, contributes to understanding of empirical regularities and the formulation and evaluation of policy. Myopia and nonstandard preferences are core to Chapter 4, a potential explanation to some results in Chapter 6, and in Chapter 2 I consider the role of a myopic policymaker.

Finally, economic models tend to deliver fine-grained policy advice with high informational requirements. In addition, the foundation of such advice may be hard to understand, and implementation hard to accomplish. There is a clear tension between precision and practicality, and though this dissertation clearly favors the former, the latter is not neglected. This shows in Chapter 5, where the the goal is to explicitly construct a simple formula for the SCC. The numerical section of the Chapter 4 considers similar easier-to-determine, but mostly easier-to-implement rules, and explores, as Chapter 5, the extent to which those less-precise results deviate from the result from more fine-grained analyses.

The remainder of the dissertation proceeds as follows. In Chapter 2 I assess under what conditions unilateral policy can prevent global emission concentrations from rising to levels deemed unsustainable. I adopt a two-country (home/foreign), two-sector framework of directed technical change with an environmental externality. In this framework, a final good is produced using a clean and a dirty intermediate, where the latter causes emissions, which degrade the environment. Scientists improve sector-specific machine quality over time, and direct their research efforts to the sector with the highest expected return. There is free trade in intermediates across countries, machine quality improvements immediately spill over across borders, yet, due to the lack of international enforcement of patent rights, scientists' incentives depend on local demand only. Finally, only one of the countries (home) implements environmental policy. To achieve sustainable growth, curbing emission growth in the foreign country is key. This in turn requires sufficient substitutability across goods, and growth to take place in clean instead of dirty sectors. A country can thus implement sustainable growth if it can redirect global innovation to the clean sector. This is the case if the home country is either very innovative on its own, or large enough to sufficiently impact industry location, such that it can redirect innovation in foreign. The latter policy does require a certain degree of sophistication of the policymaker; if the policymaker is myopic, or does not recognize the importance of innovation, he will never implement policies that redirect innovation in foreign. I calibrate the model, and find that the US or EU alone are too small to unilaterally redirect global innovation. A coalition of Kyoto Annex B countries with binding targets does not drive global innovation; it is sizeable enough to redirect innovation outside the coalition and thereby global long-run growth to the clean sector. This does, however, require very high tax rates. Larger coalitions require lower tax rates to implement sustainable growth.

Chapter 3 analyzes second-best optimal environmental policy responses to real and financial shocks in a two-period partial equilibrium model with heterogeneous firms, an environmental externality, and credit constraints. Credit constraints limit investment in emission-reducing technologies. To alleviate the constraint and encourage investment, the second-best optimal environmental tax should be set below the Pigouvian level. The optimal tax response to real and financial shocks then depends on how the shocks affects the size of the environmental and credit market failures and the effectiveness of the tax in alleviating these market failures. Under mildly restrictive assumptions on functional forms, the optimal response to a (persistent) negative productivity shock or a tightening of credit is to reduce the emission tax. These results are informative for how climate change policy should optimally change with the business cycle.

In Chapter 4 I explore the implications of good-specific habit formation for the adjustment of consumption towards a new consumption bundle. Habits affect consumers in two ways. First, they act as a benchmark against which current consumption is evaluated, and thereby negatively affect utility. Second, they cause persistence in good-specific consumption. For this second reason, with habit formation, any shift within the consumption bundle will be slow. In a context where consumers do not internalize the habit formation process I then ask whether from a welfare perspective, this adjustment is too slow or too fast. Put differently, is there room for a welfare-improving policy intervention, and does this intervention speed up adjustment to a new consumption bundle, or allow for a smoother transition path? I find that if the good-specific habit persistence effect is especially strong, a rapid shift to a new consumption bundle is optimal, while if the utility effect dominates, a slow transition is preferred. The optimal path of good-specific taxes or subsidies then depends on whether goods are produced under perfect competition or by monopolistic firms, as the strategic behavior of a monopolistic producer speeds up the transition to begin with. Insights in this chapter are general, yet are informative regarding the speed at which to introduce a carbon tax in the presence of habit formation. I apply the framework to water use restrictions in California and find that the mandate, which required large immediate water use reductions, increased the welfare cost of the transition by 6 percent. Finally, I propose two easy-to-implement rule of thumb policies that achieve welfare levels close to the one achieved under the optimal adjustment path.

In Chapter 5 we develop a simple closed-form formula to compute the social cost of carbon (SCC). This approach is distinct from the typical approach in the literature, which typically uses large-scale computational Integrated Assessment Models (IAM). The simple formula performs well; it explains the parameter-driven SCC variation of a mainstream IAM without systematic bias. The formula offers a more intuitive understanding of the core determinants of the cost of CO_2 emissions. We use the formula to construct a distribution of SCC's, and develop an analytic breakdown and quantification of how different sets of parameters contribute to the SCC distribution. We find that economic variables in particular contribute to the right-skewedness of the SCC distribution, uncertainties regarding the carbon cycle and temperature adjustment parameters contribute relatively little.

Chapter 6 is an empirical assessment of the effect of car registration and road taxes on vehicles purchase decisions. We construct a simple model that generates predictions regarding the effect of fiscal policies on average CO_2 emissions of new cars, and then test the model empirically. We use a large database of vehicle-specific taxes to construct measures for the level and CO_2 sensitivity of registration and road taxes, across the EU15 countries, over the period 2001-2010. We find that over this period, across the EU, average registration taxes fell, and registration and road taxes became more dependent on vehicle CO_2 emissions. We then use these constructed measures to estimate the effect of fiscal policies on average CO_2 of new vehicles. We find that the increase in the CO_2 dependence of registration taxes reduced the CO_2 emission intensity of the average car, partly through and induced increase in the share of diesel cars. As diesel vehicles emit more harmful local pollutants than equivalent petrol vehicles, the increase in the CO_2 dependence of registration taxes thus likely contributed to an increase in local pollution. Higher fuel taxes lead to the purchase of more fuel-efficient cars, higher annual taxes have no or an adverse effect.

Chapter 2

THE UNILATERAL IMPLEMENTATION OF A SUSTAINABLE GROWTH PATH WITH DIRECTED TECHNICAL CHANGE

Abstract

We determine the conditions under which unilateral policies can implement global sustainable growth in a dynamic two-country directed technical change framework. Domestic climate policies alter the structure of domestic and foreign production and thereby innovation incentives across countries. Implementing sustainable growth requires redirecting global innovation to the nonpolluting sector. If most innovation takes place in the foreign country, policies must redirect foreign innovation by relocating clean production to foreign. A calibration exercise suggests that the US or EU alone are too small to implement sustainable growth. A coalition of Annex I countries that ratified the Kyoto protocol can implement sustainable growth, yet required tax rates are very high.

2.1 Introduction

In the past decade, many countries have announced and implemented climate policies. Examples are the European Emission Trading System, launched in 2005 and operational in 28 countries, Germany's Energiewende and California's Global Warming Solutions Act. More recently, United States President Obama released his Clean Power Plan, which aims to reduce CO_2 emissions to 32 percent below 2005 levels by 2030. These individual countries' and states' actions followed years of unsuccessful climate negotiations at the global stage, where thus far no binding agreement on emission reductions has been signed.[1]

Such unilateral policies are, however, still viewed as inferior to a global climate policy. The main reason is that unilateral policies cause carbon leakage; emission reductions in one country may increase emissions elsewhere, undermining the effectiveness of policy. For example, the introduction of carbon taxes in one region will likely induce carbon-intensive industries to relocate to areas with less stringent climate policy (Babiker, 2005; Burniaux and Martins, 2012).[2] In these areas, the expansion of carbon-intensive industries may also encourage further innovation in carbon-intensive technologies, potentially exacerbating the leakage problem in the long run (Di Maria and Smulders, 2005; Di Maria and van der Werf, 2008; Gerlagh and Kuik, 2014; Golombek and Hoel, 2004; Hemous, 2012). Hence, even if a unilateral carbon tax reduces emissions today, it may be unable to prevent future emission growth globally, rendering the global economic growth trajectory unsustainable.

In this chapter, we determine under what conditions unilateral policies can prevent global emission concentrations from rising to levels deemed unsustainable. We propose a two-country extension of the Acemoglu et al. (2012) two-sector framework of directed technical change in the presence of an environmental externality. In the Acemoglu et al. (2012) framework, a final good is produced using a clean and dirty intermediate. These intermediates are in turn produced using labor and sector-specific machines, and the production of the dirty intermediate causes emissions, which degrade the environment. Scientists improve machine quality over time, and direct their innovation to the sector with the greatest expected return. In our extension, the countries freely trade in the clean and dirty intermediates. Machine quality improvements immediately spill over across borders, yet, as patent rights are not enforced internationally, scientist's innovation incentives depend on local machine

[1]The Paris agreement is considered an important step in the right direction. Commitments under the agreement, however, are nonbinding, and currently insufficient to prevent global average temperatures from rising beyond 2°C.

[2]See also Markusen (1975), Hoel (1996), Copeland and Taylor (2004), Levinson and Taylor (2008) and Van der Werf and Di Maria (2012).

demand. These assumptions are strong, yet offer a clear setup to analyze the core mechanisms. We explicitly consider asymmetric countries; countries may inhabit unequal quantities of laborers and/or scientists.

Contrary to earlier literature, in particular Hemous (2012), we focus on the role of country size and innovative capacity as determinants of whether unilateral policies can implement sustainable growth, and the type of policy required to do so. We find that to implement sustainable growth, curbing emission growth in the foreign country, which does not implement policy, is key. To induce substitution away from dirty goods in foreign, two requirements must be fulfilled. First, the clean good must be a sufficiently strong substitute for the polluting good. Second, the clean good must become increasingly cheaper relative to the dirty good. Reducing the relative price of the clean good requires technical change to mostly take place in the clean sector. In home, clean innovation subsidies or dirty output taxes can be used to redirect innovation to the clean sector. As long as the home country drives global growth, technology spillovers ensure that clean technologies also advance relative to dirty technologies in foreign. If instead foreign country scientists determine the direction of global growth, sustainable growth calls for policies that expand the clean sector, and thereby encourage clean innovation, in foreign. Whether unilateral policies can sufficiently expand the clean sector in foreign and thereby redirect foreign innovation depends on the initial production technologies and the relative size of the home country in terms of output. If the clean technology is relatively advanced already, less effort is required to redirect innovation to this sector. Additionally, any unilateral policy intervention will cause larger shifts in global prices and the location of production if home represents a large share of global output.

This chapter's policy recommendation to stimulate foreign clean innovation runs counter to the intuitive advice based on the static, or myopic, perspective. In the static perspective, the social planner seeks the most cost-effective solution to reduce emissions given the state of technology, and will always opt for domestic emission reductions that increase the competitiveness of the foreign dirty sector. Such domestic emission reductions thus encourage dirty innovation in foreign: if foreign innovations drive global growth these myopic policies will fail to prevent future emission growth.

Calibrating our stylized model, we find that the US or EU alone are too small to unilaterally redirect global innovation efforts towards sustainable growth. Even though a coalition of Kyoto Annex B countries with binding targets does not drive global innovation, it is sizeable enough to redirect innovation outside the coalition and thereby global long-run growth to the clean sector. This does, however, require very high tax rates. Larger coalitions require lower tax rates to implement sustainable growth.

Three elements are core to our framework and results: directed technical change, carbon leakage and the importance of locality in innovation decisions. On the topic of directed technical change, we build on the work by Acemoglu (1998; 2002), who argues that profit-motivated scientists have an incentive to develop technologies for goods that are (relatively) expensive, in high demand, and technologically advanced. In addition, Acemoglu (1998) points out the important role of international property rights protection in determining the market scientists face. Our framework features an environmental and innovation market failure; firms do not appropriate the full social return of their innovations. Jaffe et al. (2005) argue that in such a context, optimal policies comprise both a tax on pollution and an innovation subsidy. This subsidy should redirect scientists to where their social value is greatest. Using formal modeling, Gerlagh et al. (2009) and Acemoglu et al. (2012) confirm this insight and show that with directed technical change, a temporary subsidy redirecting scientists to the clean sector may be sufficient to prevent emissions from accumulating to dangerous levels.[3]

Empirical evidence for directed technical change is presented by Newell et al. (1999), who find a positive response of energy-efficiency improvements to energy prices. Popp (2002) and Aghion et al. (2012) confirm that high energy prices and a large stock of 'clean' patents spur further development of clean technologies.[4] As noted above, the unilateral implementation of a carbon tax may cause carbon leakage. Directed technical change will then affect the degree of carbon leakage in the long run (Di Maria and Smulders, 2005; Di Maria and van der Werf, 2008; Gerlagh and Kuik, 2014; Golombek and Hoel, 2004; Hemous, 2012) and possibly alter the optimal unilateral policy plan. Apart from Hemous (2012), the literature has so far not recognized that with directed technical change, sustainable growth may require the foreign country to become a clean good exporter. This is primarily due to differences in the models' underlying assumptions. Golombek and Hoel (2004) for instance, take R&D to be always pollution-saving and Di Maria and Smulders (2005) abstract from foreign innovation, ruling out the possibility of pollution-inducing technical change in the foreign country. Di Maria and van der Werf (2008) and Gerlagh and Kuik (2014) assume perfectly enforced international property rights protection, which implies that innovation becomes independent of industry location. Under this independence, any drop in the size of the polluting sector globally will push innovation away from this sector. For Di Maria and van der Werf (2008), this works in favor

[3] Aghion and Howitt (2009) reached the same conclusion in a similar, yet simplified, analysis.

[4] Acemoglu and Linn (2004) and Hanlon (2015) find evidence for directed technical change in the pharmaceutical sector and the cotton textile industry in 19th century Britain, respectively.

of finding that the 'induced-technology effect' of unilateral policy always reduces leakage.

Our analysis is most closely related to, but also importantly different from Hemous (2012). This chapter considers a 2-country (North-South) extension of the Acemoglu et al. (2012) framework; countries trade in nonpolluting and polluting goods, which are both used for final good production. Both sectors require capital, labor, and sector-specific intermediate inputs. For the polluting good this intermediate can be further separated into a clean and dirty intermediate, where the production of the latter causes environmental degradation. Both countries are endowed with a unit mass of scientists and innovation takes place in all three intermediates. Finally, patents are not traded and, in the baseline model, there are no innovation spillovers. Hemous (2012) establishes that a dirty input (carbon) tax in the North cannot implement sustainable growth: such a tax expands the polluting sector in South, and encourages Southern innovation in the dirty good. Instead, to implement sustainable growth, Hemous (2012) proposes a combination of research subsidies and trade taxes in the North, which turn North into an exporter of the polluting good and redirect innovation in the South to nonpolluting goods.

Our analysis adds the insight that the size and innovativeness of the home relative to the foreign country are crucial factors in determining whether, and what type of, unilateral policies can implement sustainable growth. First, our model explicitly accounts for the idea that, due to technology spillovers, the ability to redirect global technology through domestic innovation relies on the innovative power in home relative to foreign. Second, we describe that the ability to redirect foreign innovation depends on the size of home's demand relative to foreign. Our analysis points to three different regimes for sustainable policies, dependent on the size and innovativeness of home relative to foreign. This contrasts the analysis and findings by Hemous (2012), who assumes countries are equally innovative and thereby finds that redirecting foreign innovation is always necessary and feasible.[5]

The chapter proceeds as follows. Section 2.2 presents the model, and Section 2.3 solves for its equilibrium. The conditions under which unilateral policies can implement sustainable growth are determined in Section 2.4. Section 2.5 includes a calibration of the model and several numerical results. Results and modeling assumptions are further discussed in Section 2.6. Section 2.7 concludes. Proofs and additional calibrations can be found in the Appendix.

[5]The implications of different assumptions in this chapter and Hemous (2012) are further discussed in Section 2.6.

2.2 The model

This section introduces the basic framework. We extend the Acemoglu et al. (2012) framework to two countries: home and foreign. Each country $k \in \{h, f\}$ is endowed with a fixed amount of labor, L_k, and scientists, s_k.

Preferences and production In each country, a representative household maximizes intertemporal utility

$$U_{kt} = u\left(\mathbf{Y_{kt^+}}, \mathbf{E_{t^+}}\right) \tag{2.1}$$

where $\mathbf{Y_{kt^+}} = \{Y_{kt}, Y_{kt+1}, ..., Y_{k\infty}\}$ and $\mathbf{E_{t^+}} = \{E_t, E_{t+1}, ..., E_\infty\}$ are vectors of household final good consumption and the global pollutant stock and t is the time indicator. Utility is increasing and concave in consumption, $Y_{k\nu}$, and decreasing and concave in the pollutant stock, $E_{k\nu}$, with $\nu \geq t$. We assume there exists some finite level of the emission stock $\bar{E} > 0$ such that reaching this level is infinitely costly in terms of utility: $\lim_{E_\nu \to \bar{E}} u\left(\mathbf{Y_{kt^+}}, \mathbf{E_{t^+}}\right) = -\infty$ for any $\nu \geq t$. This property can be interpreted in two ways. First, limited substitutability between environmental and man-made goods will increase the marginal value of an environmental good as the economy grows over time and the good gets depleted. In this case, $\bar{E}$ may represent the threshold level of pollution at which the good is fully depleted, and where the marginal amenity value is infinitely high (Gerlagh and van der Zwaan, 2002; Drupp, 2015). Second, $\bar{E}$ can be interpreted as an agreed-upon limit on cumulative emissions, such as the target to limit global warming to 2 degrees centigrade. In this context, $E_\nu < \bar{E}$ is a direct constraint on policy, and passing $\bar{E}$ implies policy goals have not been met.

The utility function above is very general, and for the analysis below there is no need to further specify its functional form.[6] The core property relevant to our analysis is that it is always optimal to prevent the pollutant stock from growing over time and passing the threshold level $\bar{E}$. The remainder of the analysis will focus on unilateral policies that satisfy this necessary condition for policy optimality.

The final good is produced competitively using clean, c, and dirty, d, intermediate goods according to

$$\tilde{Y}_{kt} = \left(Y_{kct}^{\frac{\varepsilon-1}{\varepsilon}} + Y_{kdt}^{\frac{\varepsilon-1}{\varepsilon}}\right)^{\frac{\varepsilon}{\varepsilon-1}}, \tag{2.2}$$

where the tilde on Y_{kt} indicates we are dealing with production of the country k final good. $\varepsilon \in (0, \infty)$ is the elasticity of substitution between the two intermediates and Y_{kjt} is the quantity of intermediate $j \in \{c, d\}$ used in country k final good production.

[6]The utility function used in Acemoglu et al. (2012) is a more specific version of (2.1).

Throughout this chapter, we assume the two intermediates are substitutes ($\varepsilon > 1$), i.e., the clean intermediate provides a service similar to the dirty intermediate and can therefore substitute for the dirty intermediate and the functions it performs. Intermediate goods are competitively produced using labor, L_{kjt}, and a continuum of sector-specific machines x_{kjit}, of quality A_{kjit}:

$$\tilde{Y}_{kjt} = L_{kjt}^{1-\alpha-\beta} \int_0^1 A_{kjit}^{1-\alpha} x_{kjit}^{\alpha} di, \tag{2.3}$$

where $i \in [0, 1]$ denotes the machine type, $\alpha, \beta \in (0, 1)$ and $\alpha + \beta < 1$.[7] The production of each machine requires $\psi > 0$ units of the final good Y_{kt}. Labor is perfectly mobile across sectors, but immobile across countries, so that labor market clearing requires

$$L_{kct} + L_{kdt} = L_k. \tag{2.4}$$

We allow for trade in intermediate goods only and assume trade is balanced at every point in time:

$$p_{ct}\left(Y_{kct} - \tilde{Y}_{kct}\right) + p_{dt}\left(Y_{kdt} - \tilde{Y}_{kdt}\right) = 0, \tag{2.5}$$

where p_{jt} is the intermediate j world market price. Intermediate goods market clearing then requires

$$Y_{hjt} + Y_{fjt} = \tilde{Y}_{hjt} + \tilde{Y}_{fjt} \tag{2.6}$$

for both $j \in \{c, d\}$, and final good consumption equals production, minus inputs used for machine production: $Y_{kt} = \tilde{Y}_{kt} - \psi \left[\int_0^1 x_{kcit} di + \int_0^1 x_{kdit} di\right]$.

Innovation Improvements in machine quality generate growth. At the beginning of every period, each scientist decides what sector to innovate in. Within this sector, the scientist is randomly allocated to one machine, and each machine is allocated to at most one scientist. If innovation is successful, which happens with probability z, the new machine quality is $1 + \gamma > 1$ times the quality in the previous period and the scientist receives a 1-period patent for his achievements. We assume property rights are not enforced across borders. Hence, a scientist can only profitably sell his patent to a local machine producer. In the other country, the innovation is copied immediately and the machine is produced competitively. As machines are

[7] We implicitly assume a fixed factor in production, normalized to unity. This fixed factor represents physical limits to production, in terms of land, infrastructure, and e.g. for clean energy production, wind or the amount of solar radiation. In this context, β represents the income share of the fixed factor. For $\beta \to 0$, the production function approaches the intermediates production function in Acemoglu et al. (2012), where, in equilibrium, output is CRS to labor. With international trade, price differences across countries, caused by productivity differences or output taxation, then lead to a specialization of (at least) one country in the production of a single good (Ricardian trade). Our results are robust to the case where $\beta = 0$ (detailed proofs available on request).

not traded, this set of assumptions implies that a scientist's innovation decision is driven by local machine demand only. Simultaneously, technology spillovers are full and immediate; machine qualities are equal across countries at all times. These assumptions are strong, and in Section 2.6 we discuss the implications of alternative assumptions, such as (im)perfect international property rights protection, and slow technology spillovers. If innovation is unsuccessful, no patent is granted and the machine is produced competitively with the previous period quality.

Market clearing for scientists reads

$$s_{kct} + s_{kdt} = s_k. \tag{2.7}$$

Environment Emissions are caused by the production of the dirty intermediate. We assume a single, global level of the emission stock and a common emission intensity of dirty good production in home and foreign. The emission stock evolves according to

$$E_{t+1} = f\left(\tilde{\mathbf{Y}}^{\mathbf{W}}_{\mathbf{dt}^-}\right), \tag{2.8}$$

where $\tilde{\mathbf{Y}}^{\mathbf{W}}_{\mathbf{dt}^-} = \left\{\tilde{Y}^W_{d-\infty}, ..., \tilde{Y}^W_{dt-1}, \tilde{Y}^W_{dt}\right\}$, $\tilde{Y}^W_{dt} \equiv \tilde{Y}_{hdt} + \tilde{Y}_{fdt}$, $f_{\tilde{Y}^W_{dv}} \geq 0$ for $v \leq t$ with strict inequality for $v = t$, and $\lim_{v\to-\infty} f_{\tilde{Y}^W_{dv}} = 0$. In addition, we assume $E_0 < \bar{E}$. The time $t+1$ emission stock is increasing in time t global dirty good production.[8] The stock may be persistent: emissions from dirty good production today may affect the emission stock far in the future, yet will eventually dissipate. The above law of motion of the emission stock generalizes the specification used by Acemoglu et al. (2012) and the alternative proposed by Hourcade et al. (2012), which is more closely based on the climate science models.

The model is stylized, and thus requires some flexibility and caution when mapping its structure to real-world tradeoffs in production and innovation. The final good represents a basket of goods and services, ranging from food to entertainment, transport and energy. The intermediate inputs then represents the clean and dirty technologies that are close substitutes in producing these final goods or services. Take for instance vehicle miles traveled as a final good. Vehicle miles traveled is produced using cars. There are large differences between the emission intensity of gasoline-guzzling and electric cars; the former can be considered dirty, and the latter clean. Production of both types of cars takes place in both countries, and requires labor and machines. Scientists make these machines more efficient. Innovations in

[8]We define emissions as originating from dirty good production. As we assume the pollutant is global, with equal emission intensities across countries, and $\tilde{Y}^W_{dt} = Y^W_{dt}$, all results carry over if emissions are instead caused by the use of dirty goods as inputs in final good production.

vehicle battery technology, for example, constitute technical progress in the clean sector.[9]

In Section 2.6, we further elaborate on the interpretation of our stylized model in a policy context.

2.3 Equilibrium

Next we solve for the equilibrium of the model. We consider three types of policy tools: intermediate input taxes τ_{kjt}, intermediate output taxes $\tilde{\tau}_{kjt}$, and innovation subsidies q_{kjt}. Intermediate input taxes raise the cost of using intermediates as inputs in final output to $p_{jt}\tau_{kjt}$. Output taxes are taxes on the production of intermediates, and reduce the price producers receive for their intermediates to $p_{jt}\tilde{\tau}_{kjt}^{-1}$.[10] Finally, sector-specific innovation subsidies raise the expected return to innovation to q_{kjt} times the pre-subsidy return. All taxes and subsidies are defined as gross rates. For instance, an intermediate input tax is zero whenever $\tau_{kjt} = 1$ and positive for $\tau_{kjt} > 1$.

These input and output taxes have a direct analogy in the context of carbon taxation. Whenever carbon is emitted in the production process, input and output taxes on dirty goods can be compared to consumption-based emission taxes and territorial carbon taxes, respectively.[11] The former fall on all worldwide emissions, if these are attributed to domestic consumption. The latter fall on domestic emissions, irrespective of whether these emissions can be attributed to domestic or foreign consumption. This distinction is politically important, and contentious (Victor et al., 2014). In a model with no trade, the two types of taxes are equivalent, as for both intermediates, production must equal consumption.

We assume that in both countries monopoly distortions are corrected by an appropriate subsidy granted to machine users. This amounts to a subsidy rate of $(1 - \alpha)$ on machines sold by monopolists.[12] Throughout the exposition, we abstract

[9] A second example can be found in electricity, which is produced using non-fossil (clean) and fossil-using (dirty) technologies. Now, solar panels (or windmills) and coal plant equipment are the traded intermediates. Improvements in solar cells are clean innovation; an example of dirty innovation is an improvement in the durability of electrical generators that reduces the downtime for maintenance.

[10] We choose to focus on output and input taxation and abstract from trade taxes or subsidies. Any pattern of trade and equilibrium prices implemented by a particular combination of input and output taxes can also be implemented by an input or output tax alone, combined with trade taxes and subsidies. For instance, a dirty intermediate input tax is equivalent to a dirty intermediate output tax combined with an import tariff and export subsidy equal to the intermediate tax rate. In the context of carbon taxation this latter combination of import tariffs and export subsidies is known as a full border carbon adjustment.

[11] An example is the emission of CO_2 in the production of steel. If the main source of carbon emission is the use of a good, for example cars, the interpretation is a bit more subtle. See Section 2.6 for a discussion.

[12] This assumption mainly serves to simplify the exposition. Also, without this subsidy, use of unpatented machines would exceed use of patented machines. Unless we make additional assumptions we would then arrive at the counterintuitive result that a country has a comparative advantage in the sector that, relative to the other country, it has innovated little in.

from subsidies on intermediate production and input use, focusing on positive taxes instead.

We first solve for the static equilibrium where we take the quality of machines as given, and evaluate how input and output taxes affect demand, supply, and trade. Next, we take a closer look at the scientist's trade-off, and determine the effect of input and output taxes and innovation subsidies on innovation decisions.

2.3.1 The static equilibrium

Final good producers optimize their input mix by equating the marginal return to intermediate Y_{kjt} to its tax-inclusive price $\tau_{kjt}p_{jt}$. By (2.2) country k relative demand for intermediates reads

$$\frac{Y_{kct}}{Y_{kdt}} = \left(\frac{p_{ct}}{p_{dt}}\right)^{-\varepsilon} \left(\frac{\tau_{kct}}{\tau_{kdt}}\right)^{-\varepsilon}. \tag{2.9}$$

The introduction of a positive intermediate input tax on the dirty intermediate will, given the world relative price p_{ct}/p_{dt}, increase demand for the clean intermediate relative to dirty. The final good price in country k then equals $p_{kt} = \left(p_{ct}^{1-\varepsilon}\tau_{kct}^{1-\varepsilon} + p_{dt}^{1-\varepsilon}\tau_{kdt}^{1-\varepsilon}\right)^{\frac{1}{1-\varepsilon}}$. For global relative intermediate demand we find

$$\frac{Y_{ct}^{W}}{Y_{dt}^{W}} = \left(\frac{p_{ct}}{p_{dt}}\right)^{-\varepsilon} F_t, \tag{2.10}$$

where we use (2.5) and define $Y_{jt}^{W} \equiv Y_{hjt} + Y_{fjt}$ as world demand for intermediate j. F_t is a factor that corrects for intermediate input taxes in home, and the share of home in global intermediates demand. More specifically, F_t is defined as

$$F_t \equiv \frac{I_t^R + V_t^R}{\left(\tau_{hct}/\tau_{hdt}\right)^{\varepsilon} I_t^R + \left(\tau_{fct}/\tau_{fdt}\right)^{\varepsilon} V_t^R},$$

with

$$I_t^R \equiv \frac{p_{ct}Y_{hct} + p_{dt}Y_{hdt}}{p_{ct}Y_{fct} + p_{dt}Y_{fdt}} \text{ and } V_t^R \equiv \frac{\left(\tau_{hct}/\tau_{hdt}\right)^{\varepsilon} + \left(p_{ct}/p_{dt}\right)^{1-\varepsilon}}{\left(\tau_{fct}/\tau_{fdt}\right)^{\varepsilon} + \left(p_{ct}/p_{dt}\right)^{1-\varepsilon}}.$$

We can then make two observations. First, global relative demand for intermediates, Y_{ct}^{W}/Y_{dt}^{W}, lies in between relative demand in the two countries, Y_{hct}/Y_{hdt} and Y_{fct}/Y_{fdt}. This follows from the fact that F_t always lies in between $\left(\tau_{hct}/\tau_{hdt}\right)^{-\varepsilon}$ and $\left(\tau_{fct}/\tau_{fdt}\right)^{-\varepsilon}$. Suppose that intermediate output taxes are zero in foreign. Then, the introduction of a positive dirty intermediate input tax in home does, for given relative prices, not only reduce relative demand for the dirty intermediate in home, but also globally: with $\tau_{fct}/\tau_{fdt} = 1$ and $\tau_{hct}/\tau_{hdt} < 1$ we have $F_t > 1$ and $Y_{hct}/Y_{hdt} > Y^W_{ct}/Y^W_{dt} > Y_{fct}/Y_{fdt}$. Second, the introduction of an intermediate input tax in home will have a larger effect on global relative intermediates demand the larger is home compared to foreign (i.e., the larger is home's share in the value of global intermediates output and hence demand). If home is large, I^R_t is large, which implies F_t is close to $(\tau_{hct}/\tau_{hdt})^{-\varepsilon}$, and thus Y^W_{ct}/Y^W_{dt} is close to Y_{hct}/Y_{hdt}.[13] Both observations are intuitive: a shift in home demand away from the dirty good will also shift global demand away from this good, and more so if home demand represents a large share of global demand.

Intermediate good producers demand machines until the marginal return to machines equals the machine price. With a subsidy rate of $(1-\alpha)$ on machines sold by monopolists, the cost of a machine to intermediate good producers always equals machine production cost, ψp_{kt}. By (2.3) demand for machine ji in country k then reads

$$x_{kjit} = p_{kt}^{-\frac{1}{1-\alpha}} p_{jt}^{\frac{1}{1-\alpha}} \tilde{\tau}_{kjt}^{-\frac{1}{1-\alpha}} L_{kjt}^{\frac{1-\alpha-\beta}{1-\alpha}} A_{jit} \left(\frac{\alpha}{\psi}\right)^{\frac{1}{1-\alpha}}. \tag{2.11}$$

Intermediate output taxes, $\tilde{\tau}_{kjt}$, affect machine demand directly. By reducing the marginal return to machine use, they reduce machine demand for given world intermediate prices. Also, positive intermediate input taxes are detrimental for machine demand, as they increase the price of final output, p_{kt}, and thereby machine production cost and prices. Profit-maximizing monopolists charge a constant markup over marginal cost. This gives a revenue per machine of $\psi p_{kt}/\alpha$, which with (2.11), pins down profits for the machine-producing monopolist at

$$\pi_{kjit} = (1-\alpha)\, p_{kt}^{-\frac{\alpha}{1-\alpha}} p_{jt}^{\frac{1}{1-\alpha}} \tilde{\tau}_{kjt}^{-\frac{1}{1-\alpha}} L_{kjt}^{\frac{1-\alpha-\beta}{1-\alpha}} A_{jit} \left(\frac{\alpha}{\psi}\right)^{\frac{\alpha}{1-\alpha}}. \tag{2.12}$$

Profits increase in machine demand, which in turn is higher the greater is machine productivity, A_{jit}, and the marginal return to machine use, $p_{jt}^{\frac{1}{1-\alpha}} \tilde{\tau}_{kjt}^{-\frac{1}{1-\alpha}} L_{kjt}^{\frac{1-\alpha-\beta}{1-\alpha}}$. Labor is mobile across sectors, and its allocation is determined by where it earns the greatest marginal return. By (2.3) and (2.11) the marginal return to labor in sector j reads

$$MRL_{kjt} = (1-\alpha-\beta)\, p_{kt}^{-\frac{\alpha}{1-\alpha}} p_{jt}^{\frac{1}{1-\alpha}} \tilde{\tau}_{kjt}^{-\frac{1}{1-\alpha}} L_{kjt}^{-\frac{\beta}{1-\alpha}} A_{jt} \left(\frac{\alpha}{\psi}\right)^{\frac{\alpha}{1-\alpha}}. \tag{2.13}$$

A_{jt} is the sector j average machine quality, and captures productivity, or the level of

[13] If $I^R_t \to \infty$, the framework approaches a single-country model where home is the sole country. Then $F_t \to (\tau_{hct}/\tau_{hdt})^{-\varepsilon}$, which gives $Y^W_{ct}/Y^W_{dt} \to Y_{hct}/Y_{hdt}$. Likewise, for $I^R_t \to 0$ we have $F_t \to (\tau_{fct}/\tau_{fdt})^{-\varepsilon}$, and $Y^W_{ct}/Y^W_{dt} \to Y_{fct}/Y_{fdt}$.

technology, in sector j. It is defined as average machine quality

$$A_{jt} \equiv \int_0^1 A_{jit} di. \tag{2.14}$$

The marginal return to labor in a sector falls in the amount of labor employed in this sector. Labor market equilibrium then requires marginal return to be equal across sectors. This gives

$$\frac{L_{kct}}{L_{kdt}} = \left(\frac{p_{ct}}{p_{dt}}\right)^{\frac{1}{\beta}} \left(\frac{\tilde{\tau}_{kct}}{\tilde{\tau}_{kdt}}\right)^{-\frac{1}{\beta}} \left(\frac{A_{ct}}{A_{dt}}\right)^{\frac{1-\alpha}{\beta}}. \tag{2.15}$$

Finally, by (2.3) and (2.11), intermediate j country k production reads

$$\tilde{Y}_{kjt} = p_{kt}^{-\frac{\alpha}{1-\alpha}} p_{jt}^{\frac{\alpha}{1-\alpha}} \tilde{\tau}_{kjt}^{-\frac{\alpha}{1-\alpha}} L_{kjt}^{\frac{1-\alpha-\beta}{1-\alpha}} A_{jt} \left(\frac{\alpha}{\psi}\right)^{\frac{\alpha}{1-\alpha}}, \tag{2.16}$$

which gives global relative supply of intermediates

$$\frac{\tilde{Y}_{ct}^W}{\tilde{Y}_{dt}^W} = \frac{A_{ct}}{A_{dt}} \left(\frac{p_{ct}}{p_{dt}}\right)^{\frac{\alpha}{1-\alpha}} \frac{K_t \tilde{\tau}_{hct}^{-\frac{\alpha}{1-\alpha}} L_{hct}^{\frac{1-\alpha-\beta}{1-\alpha}} + L_{fct}^{\frac{1-\alpha-\beta}{1-\alpha}}}{K_t \tilde{\tau}_{hdt}^{-\frac{\alpha}{1-\alpha}} L_{hdt}^{\frac{1-\alpha-\beta}{1-\alpha}} + L_{fdt}^{\frac{1-\alpha-\beta}{1-\alpha}}}, \tag{2.17}$$

where we define $K_t \equiv \left(p_{ht}/p_{ft}\right)^{-\frac{\alpha}{1-\alpha}}$. Global relative intermediates supply is a function of relative productivity, A_{ct}/A_{dt}, relative intermediates prices, p_{ct}/p_{dt}, and the labor allocation in the two countries. Greater productivity in the clean sector, higher clean intermediate prices and high employment in the clean sector all increase the relative supply of clean intermediates. Similarly, high dirty sector productivity, prices and employment reduce global production of clean intermediates relative to dirty. Home labor is corrected by two factors. The first, K_t, corrects for differences in machine prices across countries. Machines are produced using final output. If $p_{ht}/p_{ft} > 1$, final output, and thus machines, are more expensive in home than in foreign. This gives a lower machine use per unit of labor, and thereby a lower output per unit of labor, in home. Differences in final output prices are caused by differences in intermediate input tax rates across countries, where higher input tax rates result in higher final output prices. Second, a high intermediate j output tax, $\tilde{\tau}_{kjt}$, reduces the return to j production. Firms will demand fewer machines, which again lowers output per unit of labor.

The equilibrium labor allocation and relative prices are jointly determined by market equilibrium on the global intermediate goods market, through (2.6), (2.10) and (2.17), and labor market, through (2.4) and (2.15). The laissez-faire equilibrium can then be solved in a rather straightforward manner. Next, we summarize the effect of unilateral policies on the equilibrium labor allocation, prices, and the pattern of trade.

Laissez-faire equilibrium In laissez-faire, intermediate input and output taxes are zero in both home and foreign. This gives $\tilde{\tau}_{kjt} = \tau_{kjt} = 1$ for both $k \in \{h, f\}$ and $j \in \{c, d\}$. Final and intermediate good producers then face identical prices in both countries and global relative demand for intermediates equals relative demand in the individual countries (see (2.9)):

$$\frac{Y_{ct}^W}{Y_{dt}^W} = \frac{Y_{kct}}{Y_{kdt}} \text{ and } \frac{Y_{ct}^W}{Y_{dt}^W} = \left(\frac{p_{ct}}{p_{dt}}\right)^{-\varepsilon}. \tag{2.18}$$

Also relative intermediates supply is equal across countries:

$$\frac{\tilde{Y}_{ct}^W}{\tilde{Y}_{dt}^W} = \frac{\tilde{Y}_{kct}}{\tilde{Y}_{kdt}} \text{ and } \frac{\tilde{Y}_{ct}^W}{\tilde{Y}_{dt}^W} = \left(\frac{p_{ct}}{p_{dt}}\right)^{\frac{1-\beta}{\beta}} \left(\frac{A_{ct}}{A_{dt}}\right)^{\frac{1-\alpha}{\beta}}, \tag{2.19}$$

where we used (2.15)-(2.17). In equilibrium, the relative price reads

$$\frac{p_{ct}}{p_{dt}} = \left(\frac{A_{ct}}{A_{dt}}\right)^{-\frac{1-\alpha}{1+(\varepsilon-1)\beta}}. \tag{2.20}$$

The relative price falls in relative productivity; improvements in clean technology reduce the price of clean intermediates relative to dirty intermediates. From (2.15) and (2.20), we find that high A_{ct}/A_{dt} increase the share of labor in the clean sector:

$$\frac{L_{kct}}{L_{kdt}} = \left(\frac{A_{ct}}{A_{dt}}\right)^{\frac{\sigma}{1+(\varepsilon-1)\beta}}, \tag{2.21}$$

where $\sigma \equiv (1-\alpha)(\varepsilon-1) > 0$. In laissez-faire, no strict gains from trade exist, and we assume no trade will take place.[14] Equations (2.4), (2.16), (2.20) and (2.21) then

[14]This assumption can be substantiated by allowing for some positive infinitesimal trade costs.

determine country k clean, dirty, and final good production

$$\begin{aligned}
\tilde{Y}_{kct} &= \left(A_{ct}^{\frac{\sigma}{1+(\varepsilon-1)\beta}} + A_{dt}^{\frac{\sigma}{1+(\varepsilon-1)\beta}}\right)^{\frac{1-\beta-\varepsilon(1-\alpha-\beta)}{\sigma}} A_{ct}^{\frac{\varepsilon(1-\alpha)}{1+(\varepsilon-1)\beta}} L_k^{\frac{1-\alpha-\beta}{1-\alpha}} \left(\frac{\alpha}{\psi}\right)^{\frac{\alpha}{1-\alpha}}, \\
\tilde{Y}_{kdt} &= \left(A_{ct}^{\frac{\sigma}{1+(\varepsilon-1)\beta}} + A_{dt}^{\frac{\sigma}{1+(\varepsilon-1)\beta}}\right)^{\frac{1-\beta-\varepsilon(1-\alpha-\beta)}{\sigma}} A_{dt}^{\frac{\varepsilon(1-\alpha)}{1+(\varepsilon-1)\beta}} L_k^{\frac{1-\alpha-\beta}{1-\alpha}} \left(\frac{\alpha}{\psi}\right)^{\frac{\alpha}{1-\alpha}}, \\
\text{and } \tilde{Y}_{kt} &= \left(A_{ct}^{\frac{\sigma}{1+(\varepsilon-1)\beta}} + A_{dt}^{\frac{\sigma}{1+(\varepsilon-1)\beta}}\right)^{\frac{1+(\varepsilon-1)\beta}{\sigma}} L_k^{\frac{1-\alpha-\beta}{1-\alpha}} \left(\frac{\alpha}{\psi}\right)^{\frac{\alpha}{1-\alpha}},
\end{aligned} \tag{2.22}$$

where by the absence of trade $\tilde{Y}_{kjt} = Y_{kjt}$, and $Y_{kt} = (1-\alpha)\,\tilde{Y}_{kt}$.

Unilateral policy Equilibrium relative prices, intermediate good output, $\tilde{Y}_{kjt}$, and demand, Y_{kjt}, are less straightforward to derive if the two countries implement different input and output taxes. We can, however, obtain some insights regarding equilibrium prices and the pattern of trade. Suppose home unilaterally implements intermediate input or output taxes, i.e., $\tilde{\tau}_{fjt} = \tau_{fjt} = 1$ for both $j \in \{c, d\}$, while for home we may have $\tilde{\tau}_{hjt}, \tau_{hjt} \neq 1$. We can then prove the following:

Lemma 2.1. *Define* $T_{ht} \equiv (\tau_{hct}/\tau_{hdt})^{-\varepsilon\frac{\beta}{1-\beta}}\,(\tilde{\tau}_{hct}/\tilde{\tau}_{hdt})$ *and take technologies as given. If* $T_{ht} > (<)1$*, then home is a dirty (clean) intermediate exporter, and foreign is a clean (dirty) intermediate exporter. If* $T_{ht} = 1$*, then no trade takes place and unilateral policies leave equilibrium relative prices and foreign demand, supply and labor allocation unaffected.*

Proof. Let $p_t^R \equiv p_{ct}/p_{dt}$ be the world equilibrium relative price while p_{kt}^R is the country k equilibrium relative price under autarky. By (2.9), (2.15) and (2.16), we have $p_{ht}^R = (A_{ct}/A_{dt})^{-\frac{1-\alpha}{1+(\varepsilon-1)\beta}}\, T_{ht}^{\frac{1-\beta}{1+(\varepsilon-1)\beta}}$ and $p_{ft}^R = (A_{ct}/A_{dt})^{-\frac{1-\alpha}{1+(\varepsilon-1)\beta}}$. If $T_{ht} > 1$, $p_{ht}^R > p_{ft}^R$, which implies that in our free trade equilibrium we must have $p_{ht}^R > p_t^R > p_{ft}^R$. Compared to the autarky case, the lower relative price increases home demand for, and reduces home supply of, clean relative to dirty intermediates. Hence, home becomes a clean intermediate importer and a dirty intermediate exporter. Similarly, if $T_{ht} < 1$, $p_{ht}^R < p_{ft}^R$, so $p_{ht}^R < p_t^R < p_{ft}^R$, and home exports the clean intermediate. If $T_{ht} = 1$, opening up to trade does not affect equilibrium relative prices, labor allocation, demand or supply. No trade takes place and unilateral policies leave foreign unaffected. □

T_{ht} is a measure of the degree to which home distorts intermediates demand relative to supply. By implementing a tax on dirty output in excess of the clean output tax ($\tilde{\tau}_{hct} < \tilde{\tau}_{hdt}$), home reduces the return to dirty relative to clean intermediate production, and distorts intermediate supply in favor of the clean good. Similarly, an 'excess' tax on dirty consumption ($\tau_{hct} < \tau_{hdt}$), distorts home demand in favor of clean intermediates. If T_{ht} equals unity, the demand and supply distortions cancel out and policy does not affect equilibrium relative prices. No trade will take place and foreign intermediates output and input are as in laissez-faire. If T_{ht} is below unity, the output distortion in favor of clean intermediates outweighs the shift in consumption towards clean intermediates. As a consequence, at laissez-faire prices, world relative supply of clean intermediates exceeds relative demand. Equilibrium is then re-established by a drop in p_{ct}/p_{dt}, which increases relative demand for the clean intermediate globally and causes foreign to become a dirty intermediate exporter.

2.3.2 The dynamic equilibrium

Scientists choose which sector to innovate in based on profit expectations. The patent they receive is valid only for a single period, so scientists only take the next period into account. Scientists are randomly allocated to a machine, which gives an expected machine quality if successful of $(1+\gamma)\mathrm{E}\left[A_{jit-1}\right] = (1+\gamma)A_{jt-1}$. Accounting for the probability of success, z, and noting that unsuccessful scientists will not make a profit, by (2.12), expected profits for a country k scientist innovating in sector j read

$$\Pi_{kjt} = z(1+\gamma)\,(1-\alpha)\,p_{kt}^{-\frac{\alpha}{1-\alpha}}\,p_{jt}^{\frac{1}{1-\alpha}}\,\tilde{\tau}_{kjt}^{-\frac{1}{1-\alpha}}\,L_{kjt}^{\frac{1-\alpha-\beta}{1-\alpha}}\,A_{jt-1}q_{kjt}\left(\frac{\alpha}{\psi}\right)^{\frac{\alpha}{1-\alpha}}, \tag{2.23}$$

which gives relative expected profits

$$\frac{\Pi_{kct}}{\Pi_{kdt}} = \left(\frac{p_{ct}}{p_{dt}}\right)^{\frac{1}{1-\alpha}}\left(\frac{\tilde{\tau}_{kct}}{\tilde{\tau}_{kdt}}\right)^{-\frac{1}{1-\alpha}}\left(\frac{L_{kct}}{L_{kdt}}\right)^{\frac{1-\alpha-\beta}{1-\alpha}}\frac{A_{ct-1}}{A_{dt-1}}\frac{q_{kct}}{q_{kdt}}. \tag{2.24}$$

If relative expected profits exceed unity in country k, clean sector innovation is more profitable than dirty sector innovation. As a consequence, country k scientists will relocate from the dirty to the clean sector. Similarly, if $\Pi_{kct}/\Pi_{kdt} < 1$, scientists relocate to the dirty sector. We assume that, if a scientist is indifferent, it innovates in the clean sector. Analogous to Acemoglu et al. (2012), we can identify price, market size, and technology effects. The price effect is due to p_{ct}/p_{dt}: a high relative price in sector j increases demand for machines and thereby machine profits in this sector. This effect must be corrected for output taxes, which reduce the net return to intermediates production in a sector. Hence, a relatively high output tax in sector j reduces the incentive to innovate in this sector. Next, innovation in a sector is favorable if this sector employs a large share of labor. This is called the market size effect. The final effect is the technology effect: the more advanced a sector's technology, A_{jt-1}, the greater the expected benefits from further improvements. Innovation may be subsidized, and the higher the sector j innovation subsidy, q_{kjt}, the larger the incentive to innovate in sector j.

Sector j average machine quality, then evolves according to

$$A_{jt} = A_{jt-1}\left(\gamma z s_{jt}^{W} + 1\right), \tag{2.25}$$

where A_{jt} is defined in (2.14) and $s_{jt}^{W} \equiv s_{hjt} + s_{fjt}$.

Again, we can solve for the laissez-faire equilibrium and the equilibrium under unilateral policies.

Laissez-faire equilibrium In the laissez-faire equilibrium, in addition to $\tilde{\tau}_{kjt} = \tau_{kjt} = 1$, we have $q_{kjt} = 1$ for both $k \in \{h, f\}$ and $j \in \{c, d\}$. With (2.20), (2.21) and (2.25), we reduce (2.24) to

$$\frac{\Pi_{kct}}{\Pi_{kdt}} = \left(\frac{A_{ct-1}}{A_{dt-1}}\right)^{\frac{\sigma}{1+(\varepsilon-1)\beta}} \left(\frac{\gamma z s_{ct}^{W} + 1}{\gamma z s_{dt}^{W} + 1}\right)^{-\frac{1-(\varepsilon-1)(1-\alpha-\beta)}{1+(\varepsilon-1)\beta}}. \tag{2.26}$$

As $\sigma > 0$, innovation favors the more advanced sector, which reinforces initial patterns of development. Suppose that at time $t-1$, dirty technologies are relatively advanced (A_{ct-1}/A_{dt-1} is low), such that a majority of time t scientists innovate in the dirty sector. By (2.25), dirty technologies grow faster than clean, which implies that the next period, again, a majority of scientists are active in this sector.

Multiple equilibrium scientist allocations may arise if $(\varepsilon-1)(1-\alpha-\beta) > 1$. In this case, relative expected profits are increasing in the share of scientists innovating in the clean sector. This is due to the following. The more scientists innovate in the clean sector, given A_{ct-1}/A_{dt-1}, the larger A_{ct}/A_{dt}. A greater A_{ct}/A_{dt} implies that the relative price for the clean intermediate, p_{ct}/p_{dt}, will be lower. This reduces the return to clean innovation and thereby Π_{kct}/Π_{kdt}. However, a larger A_{ct}/A_{dt} also triggers a market size effect: more labor will be employed in the clean sector, which induces additional clean sector innovation. If $(\varepsilon-1)(1-\alpha-\beta) > 1$, the latter effect dominates and an increase in the number of scientists active in a sector will further encourage research in this sector. As a consequence, multiple equilibria, where all scientists innovate in either the clean, or the dirty sector, may arise. To resolve this indeterminacy, we assume scientists coordinate on the 'clean equilibrium' with $s_{ct}^{W} =$

$s_h + s_f$ whenever both $s_{ct}^W = 0$ and $s_{ct}^W = s_h + s_f$ are an equilibrium.[15]

As has been noted above, the initial level of technologies will determine the innovation decision in laissez-faire. In the remainder of the chapter, we assume the following:

Assumption 2.1. $\frac{A_{c0}}{A_{d0}} < \min\left\{ \left(\gamma z s^W + 1\right)^{\frac{1-(\varepsilon-1)(1-\alpha-\beta)}{\sigma}}, \left(\gamma z s^W + 1\right)^{-\frac{1-(\varepsilon-1)(1-\alpha-\beta)}{\sigma}} \right\}$

where $s^W \equiv s_h + s_f$. Assumption 2.1 ensures that in the absence of intervention, for any scientist allocation, $\Pi_{kc1}/\Pi_{kd1} < 1$ for both $k \in \{h, f\}$: in both countries, scientists innovate in the dirty sector only, A_c/A_d falls over time and innovation continues to take place in the dirty sector. By (2.8) and (2.22), the persistent growth in A_d causes $\tilde{Y}_{hd} + \tilde{Y}_{fd}$ and thus emissions to grow over time. As a consequence, $E_\nu \geq \bar{E}$ at some finite time ν, which implies $U_{kt} = -\infty$. This result is symmetric to Propositions 1 and 2 in Acemoglu et al. (2012).

Assumption 2.1 captures the idea that intervention is required to curb emission growth and induce (a sufficient amount of) innovation in the clean sector. This is also resembled in real-life policy making. The OECD for instance, points at the need for incentives towards green innovation in addition to emission pricing to decouple growth from environmental degradation (OECD, 2014).

Unilateral policy Under unilateral policies we again allow for nonzero taxes and subsidies in home, while maintaining the assumption that $\tilde{\tau}_{fjt} = \tau_{fjt} = q_{fjt} = 1$ for both $j \in \{c, d\}$. Using innovation subsidies, q_{hjt}, home can, in a rather straightforward manner, redirect its scientists to the clean or dirty sector. Such subsidies affect foreign scientists' innovation incentives through the terms s_{ct}^W and s_{dt}^W. This can best be seen if home does not implement any intermediate input or output taxes, in which case (2.26) applies for foreign. Now suppose home uses subsidies to increase s_{hct} at the expense of s_{hdt}. Then for a given foreign scientist allocation, s_{ct}^W rises and s_{dt}^W falls. The effect of this rise in s_{ct}^W on the incentive of foreign scientists to innovate in the clean sector can then again be explained through price and market size effects. The increase in s_{ct}^W at the expense of s_{dt}^W results in higher A_{ct}/A_{dt} for given A_{ct-1}/A_{dt-1}. This reduces the equilibrium relative price p_{ct}/p_{dt}, and in turn reduces foreign's incentive to innovate in the clean sector. Simultaneously, a higher A_{ct}/A_{dt} pulls labor to the clean sector, increasing the return to innovation in clean. This second effect dominates if $(\varepsilon - 1)(1 - \alpha - \beta) > 1$; an increase in s_{ct}^W increases foreign scientists' incentive to innovate in the clean sector (see (2.26)). If

[15]The possibility of multiple equilibria is not specific to our model; it is also a feature of the Acemoglu et al. (2012) framework our model is based on.

$(\varepsilon-1)(1-\alpha-\beta) < 1$, the former (price) effect dominates. Now we find that substitution takes place and, if feasible, any increase in s_{hct} will be countered by an equivalent decrease in s_{fct}. For $(\varepsilon-1)(1-\alpha-\beta) = 1$ the two effects cancel out exactly and foreign innovation is independent of the home allocation of scientists, and thereby of q_{hjt}.

Through their effects on equilibrium relative prices, also intermediate input and output taxes, τ_{hjt} and $\tilde{\tau}_{hjt}$, affect scientists' innovation decisions both in home and in foreign. In addition, in home, output taxes directly affect relative returns to innovation. Substituting (2.15) in (2.24) we find

$$\frac{\Pi_{kct}}{\Pi_{kdt}} = \left(\frac{p_{ct}}{p_{dt}}\right)^{\frac{1}{\beta}} \left(\frac{\tilde{\tau}_{kct}}{\tilde{\tau}_{kdt}}\right)^{-\frac{1}{\beta}} \left(\frac{A_{ct-1}}{A_{dt-1}}\right)^{\frac{1-\alpha}{\beta}} \left(\frac{\gamma z s^W_{ct}+1}{\gamma z s^W_{dt}+1}\right)^{\frac{1-\alpha-\beta}{\beta}} \frac{q_{kct}}{q_{kdt}}. \tag{2.27}$$

The introduction of a net tax on dirty intermediate inputs $(\tau_{hct}/\tau_{hdt} < 1)$ reduces relative demand for the dirty good in home. Lower dirty intermediate demand will translate into lower dirty intermediate prices. Both in home and foreign, these lower prices lead to a drop in labor employed in the dirty sector (see (2.15)). Hence, dirty input taxes reduce the incentive to innovate in the dirty sector both directly through the price effect, and indirectly through the market size effect. Over time, an increase in clean relative to dirty sector innovation increases A_c/A_d. This in turn encourages future clean innovation in both countries.

Dirty intermediate output taxes affect innovation through the same channels. A net tax on dirty output $(\tilde{\tau}_{hct}/\tilde{\tau}_{hdt} < 1)$ increases the price of dirty goods on the world market. Both in home and in foreign this increases the incentive to innovate in the dirty sector. In home, however, the negative direct effect of output taxes on dirty innovation incentives dominates. For given prices, a tax on dirty production reduces demand for dirty machines and hence profits that flow from dirty machine varieties. All in all, dirty output taxes encourage clean innovation in home and discourage it in foreign. The following lemma summarizes the effects of home input and output taxes on foreign innovation:

Lemma 2.2. *Let $T_{ht} \equiv (\tau_{hct}/\tau_{hdt})^{-\frac{\varepsilon}{1-\beta}} (\tilde{\tau}_{hct}/\tilde{\tau}_{hdt})$ and take the s_{hjt} as given. If $T_{ht} > (<)1$, then the incentive for foreign scientists to innovate in the clean sector is increased (reduced) relative to laissez-faire. If $T_{ht} = 1$, then unilateral policies do not affect foreign scientists' incentives.*

Proof. For given s_{hjt}, s_{fjt} and A_{ct-1}/A_{dt-1}, we know A_{ct}/A_{dt}. Lemma 2.1 established that, for given A_{ct}/A_{dt}, if $T_{ht} > 1$, p_{ct}/p_{dt} rises above the laissez-faire level. By (2.27), this increases the relative return to clean innovation in foreign, increasing the incentive for its scientists to innovate in the clean sector. Likewise, if $T_{ht} < (=)1$, p_{ct}/p_{dt} falls (is unchanged), and so is Π_{fct}/Π_{fdt}. □

Lemma 2.2 implies that in addition to a 'static' leakage channel, we can identify a 'dynamic' leakage channel, which works through innovation. Dirty output taxes which cause the relative price of dirty intermediates to rise, trigger higher supply of dirty intermediates in foreign, as compared to the situation without such taxes. This increases the incentive to innovate in the dirty sector. In turn, this may increase the number of foreign scientists in the dirty sector,[16] which increases the level of dirty technology, and therefore, ceteris paribus, emissions.

2.4 Sustainable growth and unilateral policies

The previous section established that under laissez-faire the emission stock passes the threshold level $\bar{E}$ in finite time. This has major consequences in terms of welfare. Therefore, by the definition below, we consider a growth trajectory that passes the threshold unsustainable. This section then assesses whether unilateral policies can redirect the economy to a sustainable growth trajectory. As allowing the emission stock to pass $\bar{E}$ is considered infinitely costly, if feasible, the social planner will always find it optimal to implement such a growth trajectory.

Definition 2.1. *A growth path is sustainable if $E_\nu < \bar{E}$ for all ν.*

Unilateral policy can then implement sustainable growth if the following conditions are fulfilled:

Lemma 2.3. *Home can unilaterally implement a sustainable growth path at time t if and only if $\varepsilon \geq \frac{1-\beta}{1-\alpha-\beta}$, $\bar{E}$ is sufficiently large, and there exist unilateral policies that implement $s^W_{ct} > s^W_{dt}$.*

Proof. See 2.A.1. □

Though the mathematical proof is tedious, the argument is immediate. Home can always engineer an equilibrium in which it eliminates all domestic demand for, and supply of, dirty intermediates. In this equilibrium, no trade takes place, and global dirty intermediate output equals foreign laissez-faire (autarky) output and

[16] Foreign innovation in the dirty sector will rise, unless the initial equilibrium satisfies either of the following requirements: (i) All foreign scientists innovate in dirty, or (ii) All foreign scientists innovate in clean and, given the initial scientist allocation and despite the fall in p_{ct}/p_{dt}, $\Pi_{fct}/\Pi_{fdt} \geq 1$ still.

demand as described by (2.22). As it turns out, for given technologies, this equilibrium minimizes global emissions.[17] Thus, to prevent global emissions from rising over time, preventing foreign demand for dirty intermediates from rising is key. Advances in dirty technologies increase foreign demand for dirty intermediates, as they increase income and reduce the price of dirty relative to clean intermediates. Clean technology improvements reduce foreign dirty intermediate demand as long as the substitution effect from relatively cheaper clean intermediates (see (2.20)) outweighs the income effect from increased output. This is the case if $\varepsilon > (1-\beta) / (1-\alpha-\beta)$. If $\varepsilon = (1-\beta) / (1-\alpha-\beta)$, Y_{fdt} is independent of A_{ct}. Implementing a sustainable growth path thus requires $\varepsilon \geq (1-\beta) / (1-\alpha-\beta)$ and a sufficiently faster growth in A_{ct} than A_{dt}. This can only be implemented if home can, at time t, redirect the majority of global scientists to the clean sector. If home is unable to do so, A_c / A_d falls over time, which increases the relative return to dirty sector innovation, rendering home unable to redirect a sufficient number of scientists in any future period.

When A_c grows faster than A_d, the return to clean sector innovation grows relative to dirty sector innovation. Then, ceteris paribus, all innovation will take place in the clean sector in finite time. If $\varepsilon > (1-\beta) / (1-\alpha-\beta)$, this implies we will see dirty output fall over time. Finally, even if in the long run, pollution can be halted or eliminated, E_t might still rise initially. $\bar{E}$ must thus be sufficiently large for the stock of emissions to remain below this upper bound.

The next step in the analysis is to determine under what conditions home can indeed unilaterally implement $s^W_{ct} > s^W_{dt}$. Here we distinguish two cases. In the first case, home inhabits the majority of scientists. In the second case, home and foreign are either equally innovative, or foreign scientists outnumber those in home.

2.4.1 Home inhabits majority of scientists

If home inhabits the majority of scientists, i.e., if $s_h > s_f$, the domestic social planner can always redirect a sufficient number of scientists by offering an innovation subsidy to scientists in the clean sector. Alternatively it can reduce the return to dirty innovation by taxing the production of dirty intermediates. Hence, with these policy tools, home can, at any point in time, implement $s^W_c > s^W_d$. A_c / A_d will then grow over time, which increases the future return to innovating in the clean sector, both in home and in foreign. Hence, this policy intervention is only necessary for a limited period of time, and also foreign innovation will, as of some point in time, shift to the

[17] Reducing foreign dirty intermediate demand below the laissez-faire level in (2.22) requires increasing the price of dirty relative to clean intermediates, which would increase foreign (and hence global) supply of these intermediates beyond the laissez-faire level.

clean sector.[18]

Proposition 2.1. *If $\varepsilon \geq \frac{1-\beta}{1-\alpha-\beta}$, $s_h > s_f$, and $\bar{E}$ is sufficiently large, then there exist unilateral policies that redirect the global economy to a sustainable growth path. Such (temporary) policies are a clean innovation subsidy, or a tax on dirty intermediates production, or both.*

Proof. See 2.A.2 □

2.4.2 Home inhabits minority of scientists

To implement a sustainable path if $s_h \leq s_f$, home must redirect foreign scientists to the clean sector. To do so home must implement policies that increase the world market price of clean intermediates. Such a price increase will cause foreign's clean sector to expand relative to its dirty sector, which in turn increases foreign scientists' incentives to innovate in the clean sector. An example of a specific policy measure is a net tax on dirty intermediate inputs. This tax tilts home, and hence global, demand in favor of clean intermediates. Alternatively, home could introduce a net tax on clean intermediate production, which reduces home supply of this intermediate. In both cases, the increase in clean intermediates demand relative to supply increases the price of clean relative to dirty intermediates. Note that these policies turn foreign into a clean intermediate exporter and thus cause negative leakage. Unilateral policies that turn foreign into a dirty intermediate exporter will *not* implement sustainable growth. Any expansion of dirty intermediate production in foreign encourages foreign innovation in this sector, which is the exact opposite of what home aims to achieve.

Whether home can unilaterally implement a sustainable growth path depends on the size of its labor force relative to foreign's, and initial technologies. First, home produces a large share of global intermediate if its labor force is large relative to foreign's. This implies that by shifting domestic production across sectors, home causes large shifts in global intermediate supply, and thereby large changes in equilibrium relative prices. Put differently, a large country has greater control over prices and the corresponding allocation of production across countries. This is beneficial, as redirecting foreign scientists may require a sizeable expansion of foreign's clean sector.

[18] In the absence of innovation subsidies or output taxation, a dirty intermediate input tax ($\tau_{hdt} > 1$) may also be sufficient to redirect home scientists to the clean sector. By reducing global demand for dirty intermediates, such a tax reduces the world market price of dirty intermediates, and in turn the expected return to dirty innovation (see (2.24)). However, since domestic demand for the dirty intermediate cannot fall below zero, there is a limit to which home policy can alter world relative prices. Here we can show that, along the lines of Proposition 2.1 in the next subsection, a tax on dirty intermediate inputs alone can redirect home scientists to the clean sector if L_h/L_f and A_{ct-1}/A_{dt-1} are sufficiently large.

Second, if clean technologies are relatively advanced, the clean sector is already relatively large in laissez-faire. The return to clean innovation is then relatively high to begin with and a smaller shift in prices is required to sufficiently increase the return to clean innovation in foreign. Hence, we can prove the following

Proposition 2.2. *If $\varepsilon \geq \frac{1-\beta}{1-\alpha-\beta}$, $s_h \leq s_f$, and $\bar{E}$, L_h/L_f and A_{ct-1}/A_{dt-1} are sufficiently large, then there exist unilateral policies that, at time t, redirect the global economy to a sustainable growth path. Such policies reduce the relative price of dirty intermediates relative to laissez-faire.*

Proof. See 2.A.3. □

As explained above, home can more likely redirect foreign scientists the larger is its labor force relative to foreign's, and the more advanced clean technologies are relative to dirty. This immediately implies that the larger is A_{ct-1}/A_{dt-1}, the smaller the minimum L_h/L_f required. This is also confirmed by our numerical example in Section 2.5.

2.4.3 Naive policies

A social planner may not recognize the endogeneity of technical change and thereby fail to take into account the effect of its policies on innovation in general, and foreign innovation in particular. In such a situation, the social planner implements naive policies. Naive policies are unilateral policies that are optimal under the (false) presumption that innovation is exogenous. Concerning such policies, we can prove the following

Proposition 2.3. *Naive policies increase the global relative price of dirty intermediates relative to laissez-faire.*

Proof. See 2.A.4. □

The rationale behind Proposition 2.3 runs as follows. Because of the negative welfare effects of emissions, the naive planner aims to reduce global dirty intermediate output relative to laissez-faire. Such a reduction requires an equivalent drop in the use of dirty intermediates in final output globally. This latter drop causes losses in consumption, and thereby utility. For a given level of emission reduction, the social planner faces three options. First, it can implement policies that leave equilibrium relative prices, p_{ct}/p_{dt}, and thereby foreign demand for and production of dirty intermediates, unaffected. In this case, the full reduction in dirty intermediate inputs, and accompanying utility loss in terms of final output, comes at the expense of domestic consumers. Second, home can increase the price of dirty intermediates relative to clean. As a consequence, demand for dirty intermediates falls in foreign. Emission leakage will occur however: foreign dirty intermediate producers respond to the higher dirty intermediate price by increasing their production. Third, if home reduces the price of dirty intermediates relative to clean, foreign dirty intermediate demand increases relative to the laissez-faire equilibrium. So, to reach the emission reduction goal, home must reduce its own use of dirty intermediates in final goods production in excess of the reduction goal. This increases utility losses relative to the case with an unchanged price ratio. This third option can thus never be optimal: home will never implement policies that reduce the world market price of the dirty relative to the clean intermediate. Also, one can show that the first option is suboptimal: home prefers to share the utility losses from a reduced use of dirty intermediates in final output with foreign.[19]

As the naive planner does not account for the effect of taxes on innovation, the above policy is independent of the number of scientists in the two countries. From Proposition 2.2, the next corollary follows

Corollary 2.1. *If $\varepsilon \geq \frac{1-\beta}{1-\alpha-\beta}$, $s_f > s_h$ and $\bar{E}$, L_h/L_f and A_{ct-1}/A_{dt-1} are sufficiently large, then naive policies are inconsistent with optimal policies.*

Proof. By Proposition 2.2, if $\varepsilon \geq (1-\beta)/(1-\alpha-\beta)$, $s_f > s_h$ and $\bar{E}$, L_h/L_f and A_{ct-1}/A_{dt-1} sufficiently large, unilateral policies can redirect the economy to a sustainable growth path. Such policies reduce the relative price of dirty intermediates vis-a-vis laissez faire. By Proposition 2.3, naive policies implement the opposite: they *increase* in the relative price of dirty intermediates. □

This contradiction between naive and optimal policies can have far-reaching consequences. Under naive policies, the share of labor employed in foreign dirty intermediates production will increase and, by (2.24) and Assumption 2.1, all foreign scientists continue to innovate in the dirty sector. If foreign inhabits the majority of scientists, such policies will not implement a sustainable growth path. This is true even if the conditions in Proposition 2.2 were satisfied, i.e., even if implementing sustainable growth would have been feasible.

[19] If one would consider the case where $\beta = 0$, Proposition 2.3 is slightly adjusted to "Naive policies *weakly* increase the global relative price of dirty intermediates relative to laissez-faire". Corollary 2.1 below continues to apply.

2.5 Calibration

Up to this point, the analysis of unilateral policies has been analytical, allowing us to draw qualitative conclusions only. In this section, we perform a simple calibration exercise and address more quantitative issues. By seeing the model at work, this exercise enhances our understanding of the model implications. It also allows us to draw additional conclusions related to what climate coalitions are capable of implementing sustainable growth, the level of the required tax rates for sustainability, and short-run effects of unilateral policies. Given the strong assumptions of our framework, the simple trade structure, and the fact it only includes 2 abstract sectors, the exercise below should mostly be interpreted as a first inquiry into the economic significance of the mechanism at work. In 2.B.2 we take an alternative assumption regarding international property rights protection, and assess the implications of allowing scientists to patent their innovations abroad.

2.5.1 Parameter values

To enhance comparability to the Acemoglu et al. (2012) framework, parameters are chosen in line with their work. This implies we choose $\alpha + \beta = 1/3$, $\gamma z = 0.02$, $\psi = \alpha$, $L^W = 1$, and $s^W = 1$. The β parameter represents the income share of the fixed factor in intermediate output. We set $\beta = 1/30$, which is just below the 5 percent factor share of land as estimated by Valentinyi and Herrendorf (2008) and gives $\alpha = 9/30$.[20] Acemoglu et al. (2012) use three different values for ε, the elasticity of substitution between clean and dirty varieties: 3, 5 and 10. Several researchers (Hourcade et al., 2012; Papageorgiou et al., 2013; Pelli, 2011) regard these elasticities of substitution as (too) high. To acknowledge this critique, we select the lowest value: $\varepsilon = 3$.[21] For these parameter values, the condition $\varepsilon \geq (1-\beta) / (1-\alpha-\beta)$ is always satisfied. Throughout we assume that $\bar{E}$ is sufficiently high such that, if home can implement a growth path that prevents dirty output from rising in the long run, this growth path is sustainable. This implies we abstract from the question whether growth can be redirected sufficiently fast. One could reinterpret this as answering the question whether there exists some finit emission concentration level that we are able to avoid. We consider only unilateral policies, i.e., we assume that no intermediate input and output taxes or innovation subsidies are implemented in foreign: $\tau_{fjt} = \tilde{\tau}_{fjt} = q_{fjt} = 1$.

[20] Also the value of $\alpha + \beta = 1/3$ is in line with the results by Valentinyi and Herrendorf (2008).
[21] This value is in line with the findings by Papageorgiou et al. (2013).

2.5.2 Results

Figure 2.1 plots the combinations of L_h/L_f and A_{ct-1}/A_{dt-1} that allow home to implement a sustainable growth path as of time t if $s_h \leq s_f$. In line with our analytical result, given L_h/L_f, a larger A_{ct-1}/A_{dt-1} increases the likelihood that home can implement a sustainable growth trajectory. For A_{ct-1}/A_{dt-1} close to zero, i.e., clean technology that is very basic compared to dirty, no unilateral policy will be able to redirect the economy to a sustainable growth trajectory. To the contrary, if A_{ct-1}/A_{dt-1} exceeds the level implied by Assumption 2.1, growth is already sustainable in laissez-faire. Similarly, given A_{ct-1}/A_{dt-1}, the greater L_h/L_f, the more likely home can redirect foreign scientists to the clean sector. The rationale is immediate: home redirects foreign scientists through taxation policies which increases the world price of the clean intermediate. The larger is L_h/L_f, the larger is home's global output share, and the larger the effect of home taxation on the global equilibrium.

Figure 2.1: Minimum country size for implementing sustainable growth if $s_h \leq s_f$

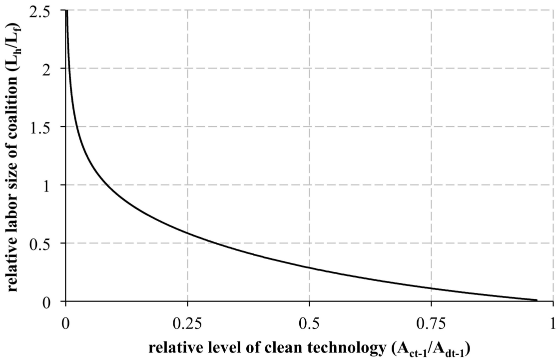


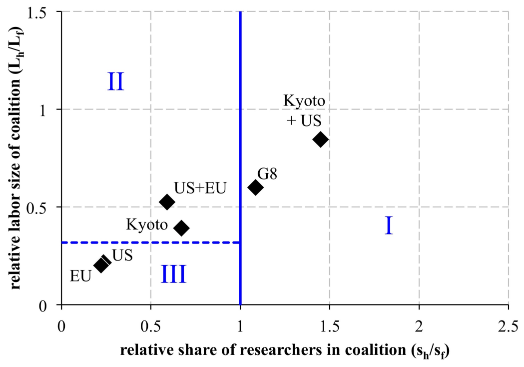
Figure 2.1 applies as long as $s_h \leq s_f$, yet is independent of the exact levels of s_h and s_f. This may seem counterintuitive at first, but is a direct consequence of the fact that home and foreign scientists are perfect substitutes, with equal productivity in innovation (see (2.25)). Figure 2.2 maps several coalitions in $\left(L_h/L_f, s_h/s_f\right)$-space. Coalition sizes are calibrated based on WEO GDP and WIPO patent data.[22] In line with Acemoglu et al. (2012), we calibrate A_{ct-1}/A_{dt-1} based on the ratio of non-fossil to fossil fuel in world energy supply. This gives $A_{ct-1}/A_{dt-1} = 0.47$.[23] In

[22]For the calibration, we re-interpret the number of labor and scientists as effective (productivity-adjusted) units. More details regarding the calibration can be found in 2.B.

[23]Under these parameter values, if in the future all scientists are redirected to the clean sector, it will take 38 years until policy is no longer required to redirect innovation to the clean sector. This is in line with the calibration results by Acemoglu et al. (2012).

Area I, $s_h > s_f$ and Proposition 2.1 applies: the coalition dominates global innovation and can implement sustainable growth by redirecting its own scientists to the clean sector. Examples of such coalitions are the countries with binding targets under the Kyoto treaty (henceforth referred to as the Kyoto coalition)[24] plus the US, or a coalition of G8 countries. Also Area II coalitions, such as the Kyoto coalition or a coalition of the EU and US, can implement sustainable growth. However, because $s_h \leq s_f$, these coalitions must redirect *foreign* innovation to the clean sector. The smaller coalitions in Area III cannot implement sustainable growth. These are the coalitions that are insufficiently innovative to redirect global growth by redirecting domestic scientists only, and also too small to redirect foreign scientists to the clean sector. The EU and US find themselves in this situation (note that in the figure, the EU and US are hard to distinguish).[25] Section 2.B.2 reproduces Figure 2.2 under the alternative assumptions that (a share of) scientists are able to profitably patent their innovation abroad. Here we show that the ability to patent all innovations abroad increases the size of Area III at the expense of Area II: unilaterally implementing a sustainable growth path becomes more difficult. Also a policy where home protects clean patents from foreign does not reduce the minimum L_h/L_f required to implement sustainable growth.

Figure 2.2: Coalitions that can (I and II) and cannot (III) implement sustainable growth



For Area I coalitions, a clean innovation subsidy is sufficient to redirect the majority of scientists to the clean sector. If the coalition does not inhabit the majority

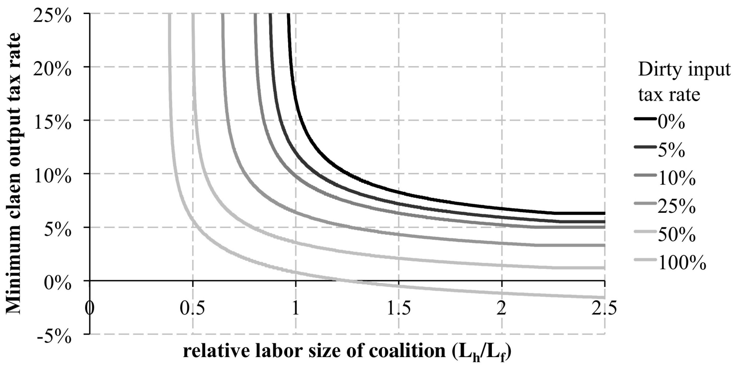
[24]This Kyoto coalition includes the EU countries, Australia, Belarus, Iceland, Japan, New Zealand, Russia, Turkey, Switzerland and Ukraine (no data was separately available for Monaco). This corresponds to all Annex I parties excluding Canada and the US.

[25]This conclusion no longer applies for very high β. In that case the calibrated labor size of the US and EU just pass the level required for implementing sustainable growth.

of scientists, but is sufficiently large (Area II coalitions), taxes on clean intermediate output, and/or dirty intermediate inputs are required to implement a sustainable growth trajectory.

Figure 2.3 takes a closer look at such tax rates. It depicts the minimum taxes required on clean intermediate output for different levels of L_h/L_f, given $A_{ct-1}/A_{dt-1} = 0.47$ and the tax rate on dirty intermediate inputs. A clean output tax below zero should be interpreted as the negative of the dirty output tax. From Figure 2.3 we learn that the larger the coalition, the lower the tax rate required to implement a sustainable growth trajectory. This is intuitive; a given tax rate has a larger effect on world supply, demand, and relative prices, if the country, or coalition, where this tax is introduced is larger. Also, if the tax rate on dirty intermediate consumption is already high, the clean output tax rate necessary to redirect a sufficient number of foreign scientists to the clean sector is lower. From Figure 2.3 we can deduce the implications of restrictions on policy. Suppose that a policymaker cannot implement input taxes. In this case, a clean output tax of 6.5% is required to implement sustainable growth if L_h/L_f is very large ($\geq$ 2.5), and no clean output tax can implement sustainable growth if $L_h/L_f < 0.96$.

Figure 2.3: Minimum tax rates for implementing sustainable growth



For the Kyoto coalition (which has $L_h/L_f = 0.39$), we find that with a 100% tax on dirty intermediate inputs ($\tau_{hdt} = 2$), the minimum tax required on clean intermediate output is 18% ($\tilde{\tau}_{hct} = 1.18$). If we reduce the tax on the use of dirty intermediate to 50%, unilaterally implementing sustainable growth is no longer feasible. As with an $A_{ct-1}/A_{dt-1} = 0.47$, expenditures on dirty intermediates represent almost 75 percent of total intermediate expenditures in laissez-faire, we consider these taxes to be high. Given the stylized nature of the calibration, translating tax rates to \$ per ton of CO_2 is not straightforward. Following the approach by Hourcade et al. (2012), a

100% tax on dirty intermediates corresponds to a tax in the range of 158 to almost 2000 $\$/tCO_2$. This result raises the question whether the unilateral implementation of a sustainable growth trajectory is politically feasible.

The next table illustrates the short run implications of unilateral policies implementing a sustainable growth path. By raising the relative price of clean intermediates, unilateral policies do not only encourage clean innovation in foreign, but also foreign demand for dirty intermediates. Put differently, policy has a dynamic effect on emission through redirecting innovation and altering A_{ct}/A_{dt}, but also a direct effect for given A_{ct}/A_{dt}.[26] As a consequence, we cannot rule out the possibility of short run emission increases. Table 2.1 depicts the short run effect of policies from Figure 2.3 on global dirty intermediate output. It decomposes the full effect from unilateral policies into an innovation and a tax effect. Here, the innovation effect is defined as the effect of policies on emissions through their effect on A_{ct}/A_{dt}. The tax effect captures the effect of intermediate input and output taxes taking technologies as given.

Table 2.1: Short run global emission effect of unilateral policies for $L_h/L_f = 1.5$

dirty input tax rate	clean output tax rate	full effect	innovation effect	tax effect
0%	8%	-1%	-3%	2%
5%	7%	-4%	-3%	-1%
10%	6%	-7%	-3%	-4%
25%	4%	-15%	-3%	-12%
50%	2%	-27%	-3%	-24%

Table 2.1 shows that the innovation effect of unilateral policies is always negative; policies redirect innovation from the dirty to the clean sector and thereby reduce emissions in the short run. The tax effect can either be positive or negative. A negative effect is more likely the larger the dirty intermediate input tax. This is intuitive, as such a tax reduces home, and thus global, demand for dirty intermediates. Table 2.1 displays the effects only for $L_h/L_f = 1.5$, yet qualitatively it holds for any L_h/L_f. In Table 2.1, the full effect is always negative: even in the short run, unilateral policies reduce emissions. In the context of Propositions 2.1 and 2.2, this implies that the requirement that $\bar{E}$ must be sufficiently high can possibly be dropped; whenever the threshold $\bar{E}$ has not yet been passed, and the emission stock is not too persistent, there exist unilateral policies that ensure this threshold will never be passed. The size of the innovation effect, however, strongly depends on the rate of innovation in

[26] Note again the timing of events. Time t policy is observed or anticipated by scientists s_{kt}, which by (2.25) affects technology, A_{jt}, and thereby time t output and pollution.

society ($\gamma z s^W$). The lower this rate, the smaller the innovation effect. With a positive effect of unilateral taxation on short-run dirty intermediate production, a smaller innovation effect may turn the total effect of unilateral policies on pollution positive in the short run.

2.6 Discussion

The model is stylized, and several assumptions were made to facilitate our analysis. Below, we discuss three of such assumptions in relation to previous literature and the expected implications of alternative assumptions for our analysis. We consider a formal discussion of such alternative setups outside the scope of the current chapter, yet as interesting and potentially fruitful avenues for future research. In addition, as the model is stylized, the interpretation of the model and its policy recommendations is, in a subtle way, dependent on the relevant policy context. We shortly discuss such interpretations, and also offer some insights regarding the characteristics of optimal policies if sustainable growth cannot be achieved.

2.6.1 Robustness under alternative model assumptions

In Di Maria and van der Werf's (2008) framework of trade, induced technical change and unilateral environmental policy, property rights are perfectly enforced internationally. In this setup, the return to innovation in a sector is independent of the location of intermediates production and, in the absence of innovation subsidies, home and foreign scientists face identical innovation incentives. Intuition would then tell us that in our framework, becoming a dirty intermediate exporter is no longer a necessary requirement for home to redirect foreign innovation to the clean sector (see Proposition 2.2). Put differently, international property rights protection expands home's set of policy options that encourage clean innovation in foreign. Perfect international property rights enforcement is, however, a very strong assumption too. Typically, licensing a patent abroad entails some additional adjustment or trade cost, and one may find the probability of success in innovation enhanced by learning spillovers from local industries. A more realistic assumption would be that scientists are responsive to global production, but more so to local production.[27] In Appendix 2.B.2 we extend our model to allow for various degrees of international property rights protection. We find that redirecting foreign scientists becomes more

[27] This assumption is supported by Dechezleprêtre and Glachant (2014), who find that for wind technologies, the marginal effect of domestic policies on home innovation is 12 times greater than foreign policies.

difficult if foreign scientists can license patents in home. Additionally, our intuition regarding Proposition 2.2 is confirmed: home can simultaneously redirect foreign scientists and export clean intermediates. Yet, the L_h/L_f ratio required for such a strategy to be effective is much higher than the L_h/L_f under the strategy described in Proposition 2.2, where home becomes a dirty intermediate exporter.

Technology spillovers are full and immediate in our framework. The presence of international technology spillovers is supported by empirical research, yet this research has also shown these spillovers are typically slow and incomplete (see for instance Coe and Helpman (1995); Jaffe and Trajtenberg (1999); Keller (2002), and Keller (2004) for a review). If, in our framework, technologies would require time to diffuse, the country with the largest research base still determines the direction of growth in the long run.[28] One can then show that if $s_h > s_f$, innovation subsidies are sufficient to redirect global innovation to the clean sector in the very long run. In the absence of technology spillovers, however, redirecting foreign innovation is the only route towards preventing emission growth in foreign. So under this alternative assumption, Proposition 2.2 and Corollary 2.1 apply for any $s_f > 0$. This conclusion is in line with Hemous (2012), who assumes no technology spillovers, and finds that to implement sustainable growth, foreign innovation should always be redirected to the nonpolluting good.[29]

A final (implicit) assumption deals with the allocation of scientists. In our framework, scientists are active either in the clean or dirty sector, and can freely move across these two sectors, without loss of productivity. This allows us to clearly define the ratio s_h/s_f that distinguishes the cases where redirecting domestic scientists is sufficient ($s_h > s_f$), or not ($s_h \leq s_f$). Here, one can argue in favor of several alternative assumptions. For example, suppose that due to intransferable skills some scientists stick to their original (dirty) sector or are more productive in this sector. In such a case, we need $s_h \gg s_f$ for redirecting domestic scientists to be sufficient to implement sustainable growth.[30] Alternatively, suppose, as in Hemous (2012), there is a third sector, e, where innovation takes place and in laissez-faire we have $s_{kc} = 0$ and $s_{kd}, s_{ke} > 0$ in both countries. Now, implementing sustainable growth by redirecting domestic scientists to the clean sector only is already feasible for some

[28]Hence, one could re-interpret the perfect spillover assumption as a long-run approximation of imperfect spillovers.

[29]In an extension, Hemous (2012) considers imperfect technology spillovers. Despite differences between his and our framework, his general conclusion regarding this case is in line with our statement above: there will be a 'race' between clean innovation in one country and dirty innovation in the other to determine whether production is clean or dirty in the long run.

[30]Naturally, if the allocation of the majority of scientists worldwide is inelastic and scientists are initially active in the dirty sector, sustainable growth can never be implemented.

$s_h \leq s_f$.[31] Hence, depending on the most realistic representation of the (elasticity of the) allocation of scientists as well as their productivity in different sectors, the cut-off ratio of s_h/s_f that determines whether domestic innovation subsidies alone are sufficient to redirect global growth may be adjusted.

2.6.2 Interpretation in policy context

As explained in Section 2.2, the final good in our model can be interpreted as a basket of goods and services, including food, transport, and energy. What matters for sustainable growth is the substitution between dirty and clean technologies producing the same good or service; e.g. the substitution between gas-guzzling and electric vehicles, and coal and renewable technologies in electricity production. For some of these substitution processes, one needs to be cautious with the precise interpretation of the model. CO_2 emissions from cars for example, are mostly due to the use, as opposed to the production, of cars. The same applies to coal plants; CO_2 is mostly emitted when coal plants are used to produce electricity, rather than during the construction of the plant, or production of the plant's equipment. As emissions in our model are a global pollutant, results are independent of whether emissions are associated with the production, or use, of the intermediate good in the final good sector. The interpretation of input versus output taxes in the context of real-world policy, however, differs importantly. When emissions occur during the production of dirty intermediates (such as steel), a dirty input tax can be interpreted as a consumption-based carbon tax, falling also on foreign emissions for imported dirty intermediates. A dirty output tax in this case is interpreted as a territorial carbon tax. If instead emissions occur during the use of a dirty intermediate (gasoline cars, coal plants), consumption-based carbon taxes and territorial carbon taxes both work as dirty input taxes. A dirty output tax would require a yet-unknown 'production-induced carbon tax'. That is, cars would be taxed at the factory's exit gate for expected emissions during the product's life cycle. Similarly, an exit-gate tax on solar panels would be an example of a clean output tax.

In our model, the introduction of a dirty output tax in home increases the incentive for dirty innovation in foreign, as it causes a shift of dirty intermediate production to foreign. An exit-gate tax for polluting vehicles moves incentives in the same direction. It reduces home production of polluting cars, and thereby increases the world market price of cars with high CO_2 emissions relative to low CO_2 emissions (i.e., reduces p_c/p_d) . This then increases production of CO_2-intensive cars in the for-

[31] As Hemous (2012) always assumes $s_h = s_f$, he finds that unilateral policy can always implement sustainable growth (the case of Proposition 2.1).

eign country, and reduces the incentive to innovate in clean vehicle technologies. In home, this incentive is increased, as production has now shifted to relatively cleaner cars.

As a final note, this chapter determines the conditions under which a country can unilaterally implement sustainable growth. Sustainable growth requires innovation to be clean in the long run. It also requires a sufficiently strong substitutability between clean and dirty goods in final output production, and a sufficiently high emission threshold $\bar{E}$. Policy intervention does not however become meaningless if sustainable growth cannot be achieved. As emissions cause a negative welfare effect in (2.1) even before $E < \bar{E}$, welfare can be improved by implementing policy that reduces emissions. In addition, the framework features a strong innovation externality, and the social return from innovating in one sector relative to another may deviate from the private return. In this case, appropriate innovation subsidies are still welfare-improving. A full analysis of such optimal policies is beyond the scope of this chapter, yet some preliminary insights can be obtained. If redirecting foreign scientists is not feasible or optimal, optimal policy is characterized by the 'naïve' policy discussed in Section 2.4.3 and Proposition 2.3, in combination with domestic innovation subsidies that direct home scientists to the preferred sector. Similarly, if, due to large social welfare gains from clean innovation, redirecting foreign scientists is optimal, home should implement policies that reduce the price of dirty intermediates as in Proposition 2.2.

2.7 Conclusion

In this chapter we determine whether, and what type of, unilateral policies can implement sustainable growth. We employ a two-country model with directed technical change, international technology spillovers, and an environmental externality. We characterize the equilibrium under laissez-faire, and the effects of unilateral policies on production and innovation, both in home and in foreign.

We find that policies that cause emission leakage, that is, increase dirty good production in foreign in response to a reduction in home, also increase the incentive in foreign to innovate in the dirty sector. This indirect effect of unilateral policies on innovation has major implications for the type of unilateral policies that implement sustainable growth. Sustainable growth requires redirecting innovation away from the dirty, towards the clean sector. This implies that if the home country dominates global innovation, an increase in domestic clean innovation suffices, while if most innovation takes place in the foreign country, redirecting foreign innovation is the prime policy concern. Appropriate policies differ considerably across the two cases: domestic innovation subsidies or a dirty output tax increase clean innovation incentives in home, yet fail to redirect foreign innovation. Instead, increasing the incentive of foreign innovators to innovate in the clean sector requires policies that sufficiently expand the size of foreign's clean sector, and turn the foreign country in a clean good exporter. Whether home can sufficiently redirect foreign innovation then depends on the size of the home country: if home produces a larger share of global output, its policies will have a larger effect on world equilibrium prices and therefore foreign production and innovation incentives. Also, the more advanced are clean technologies initially, the more likely home can redirect foreign innovation. It is vital for the policymaker to recognize the indirect effect of policy on innovation; a policymaker that does not take into account this effect will always prefer policies that cause positive emission leakage, and thus reduce the return to clean relative to dirty innovation in foreign.

Our model is stylized, yet we believe it delivers a robust core insight. To implement sustainable growth, policies should first and foremost target innovation incentives, not only within the climate coalition but potentially outside this coalition too. The need to target innovation incentives outside the coalition is relevant: a quick glance at the data reveals that three of the most innovative nations did not ratify, or have no binding targets, under the Kyoto treaty.[32] As innovators in these nations will, for a large part, determine the world's long-run growth trajectory, their incentives should be taken into account in the design of environmental policies. In this light, the US imposition of tariffs on Chinese solar panels may not only be harmful to the environment in the short run, but may also have unfavorable long-run repercussions.[33] A simple calibration exercise confirms this picture: a coalition of countries with binding targets under the Kyoto treaty is insufficiently innovative to implement sustainable growth without redirecting non-Kyoto innovation. They are capable of doing the latter, albeit at the cost of very high tax rates on use of polluting goods. Increasing the size of the coalition would allow for lower tax rates.

It is highly likely that unilateral policies remain relevant in the foreseeable future. Major challenges remain towards establishing a universal climate treaty with binding limits on emissions. And even if such a global agreement is reached, not all countries may implement the same set of policy measures.[34] Developing countries, or countries whose industries would be particularly hurt by the implementation of

[32] WIPO (2014) shows that China, the US and Japan belong to the 5 most innovative countries (by patent, trademark and industrial design counts) worldwide, where China is the fastest growing.

[33] See New York Times (2012) .

[34] The Paris agreement serves as an example of this. Though global, the agreement does not bind countries to meet targets. In addition, the agreement does not impose a universal climate policy, such as a global carbon tax. Instead, countries independently decide about their own domestic policies.

stringent environmental policies, may only cooperate conditional on certain provisions in the agreement. Differential policies across different (groups of) countries can affect trade patterns and insights obtained from the analysis of unilateral policies can be extended to such cases.

Further research could investigate the empirical relevance of this chapter's argument by assessing the relationship between carbon leakage and the spatial distribution of innovation over time. Alternatively, the framework could be extended by modeling the foreign country's policy decision and its response to domestic policies. Finally, the number of scientists in both countries is crucial, yet taken constant and exogenous. Future research could endogenize the number of scientists and take into account that the set of countries that dominate global innovation may change over time; China for instance is rapidly increasing R&D expenditures. Such added dynamics may open up additional strategies for policy, and we consider this topic in particular an interesting area for further research.

Appendix 2

2.A Proofs

To save on notation, all proofs use the following definitions for relative intermediates prices $p_t^R \equiv p_{ct}/p_{dt}$, relative technology $A_t^R \equiv A_{ct}/A_{dt}$, relative labor $L_w^R \equiv L_h/L_f$ and $L_{kt}^R \equiv L_{kct}/L_{kdt}$, and relative final goods prices $p_{wt}^R \equiv p_{ht}/p_{ft}$. Likewise, we define relative taxes $\tilde{\tau}_{kt}^R \equiv \tilde{\tau}_{kct}/\tilde{\tau}_{kdt}$ and $\tau_{kt}^R \equiv \tau_{kct}/\tau_{kdt}$, relative global intermediates production $\tilde{Y}_t^{WR} \equiv \tilde{Y}_{ct}^W/\tilde{Y}_{dt}^W$ and demand $Y_t^{WR} \equiv Y_{ct}^W/Y_{dt}^W$, and relative expected profits $\Pi_{kt}^R \equiv \Pi_{kct}/\Pi_{kdt}$. Next, we define Y_{kjt}^{LF} and $\tilde{Y}_{kjt}^{LF}$ as the country k laissez-faire equilibrium demand and supply of intermediate j, and $p_t^{R,LF}$ is defined as the laissez-faire equilibrium relative price, where (2.20) gives $p_t^{R,LF} = \left(A_t^R\right)^{-\frac{1-\alpha}{1+(\varepsilon-1)\beta}}$.

2.A.1 Proof to Lemma 2.3

As E_{t+1} is strictly increasing in $\tilde{Y}_{dt}^W$ and, absent of environmental policy, growth in $\tilde{Y}_d^W$ is strictly positive, implementing a sustainable growth path (see Definition 2.1) requires curbing growth in global dirty intermediates production. The proof then proceeds in several steps. First, we determine $Y_{dt}^{W,MIN}$, which is defined as the time t minimum equilibrium global dirty intermediates demand, for given A_{dt} and A_{ct}. If, asymptotically, $Y_d^{W,MIN}$ grows, so must Y_d^W and hence $\tilde{Y}_d^W$. Second, we show that $Y_d^{W,MIN}$ is constant or falls over time only if $\varepsilon \geq (1-\beta)/(1-\alpha-\beta)$, and growth in A^R is sufficiently faster than growth in A_d. Third, we conclude that $A_t^R > A_{t-1}^R$ only if $s_{ct}^W > s_{dt}^W$. Fourth, we prove that unless home can implement $s_c^W > s_d^W$ at time t, it will be unable to implement $s_c^W > s_d^W$ at any point in the future. Finally, we argue that by implementing $s_c^W > s_d^W$ for a sufficiently long period of time, home can, in finite time, ensure growth in A_d comes to a halt. Then, $Y_d^{W,MIN}$ is constant or declining over time, and so can $\tilde{Y}_d^W$. To separate the steps, we summarize each step in a lemma and prove them in turn.

Lemma 2.A.1. $Y_{dt}^{W,MIN} = Y_{fdt}^{LF}$

Proof. For given technologies, both foreign demand and supply of dirty intermediates are solely a function of p_t^R. By (2.4), (2.15), (2.16), and $\tilde{\tau}_{fjt} = \tau_{fjt} = 1$ for both $j \in \{c, d\}$ foreign supply of dirty intermediates reads

$$\tilde{Y}_{fdt} = \left(\left(p_t^R\right)^{1-\varepsilon} + 1\right)^{\frac{\alpha}{\sigma}} \left(1 + \left(p_t^R\right)^{\frac{1}{\beta}} \left(A_t^R\right)^{\frac{1-\alpha}{\beta}}\right)^{-\frac{1-\alpha-\beta}{1-\alpha}} A_{dt} L_f^{\frac{1-\alpha-\beta}{1-\alpha}} \left(\frac{\alpha}{\psi}\right)^{\frac{\alpha}{1-\alpha}}.$$

$\tilde{Y}_{fdt}$ is falling in p_t^R and any policy in home that reduces p_t^R increases foreign supply of dirty intermediates. Next, using (2.4), (2.5), (2.9), (2.15) and (2.16) we have

$$Y_{fdt} = \left(\left(p_t^R\right)^{1-\varepsilon} + 1 \right)^{\frac{\alpha-\sigma}{\sigma}} \left(1 + \left(p_t^R\right)^{\frac{1}{\beta}} \left(A_t^R\right)^{\frac{1-\alpha}{\beta}} \right)^{\frac{\beta}{1-\alpha}} A_{dt} L_f^{\frac{1-\alpha-\beta}{1-\alpha}} \left(\frac{\alpha}{\psi}\right)^{\frac{\alpha}{1-\alpha}}.$$

Here, one can show that whenever $p_t^R \geq p_t^{R,LF}$, Y_{fdt} is increasing in p_t^R. Now suppose home can freely set any p_t^R. If home sets $p_t^R < p_t^{R,LF}$, we find $\tilde{Y}_{fdt} > \tilde{Y}_{fdt}^{LF} = Y_{fdt}^{LF} > Y_{fdt}$. Home cannot demand nor supply a negative amount, so we must have $\tilde{Y}_{dt}^W > \tilde{Y}_{fdt}^{LF}$ for $p_t^R > p_t^{R,LF}$. Similarly, if home sets $p_t^R > p_t^{R,LF}$, $\tilde{Y}_{fdt} < \tilde{Y}_{fdt}^{LF} = Y_{fdt}^{LF} < Y_{fdt}$ and $\tilde{Y}_{dt}^W > \tilde{Y}_{fdt}^{LF}$. Finally, if home sets $p_t^R = p_t^{R,LF}$, $\tilde{Y}_{fdt} = \tilde{Y}_{fdt}^{LF} = Y_{fdt}^{LF} = Y_{fdt}$. Now, we can show $\tilde{Y}_{dt}^W \geq \tilde{Y}_{fdt}^{LF}$ by the following. First of all, whenever home demands or supplies dirty intermediates, we must have $\tilde{Y}_{dt}^W > \tilde{Y}_{fdt}^{LF}$. However, if home sets $\tilde{\tau}_{hdt} = \tau_{hdt} = \infty$ with any $\tilde{\tau}_{hct}, \tau_{hct} < \infty$ it will neither demand, nor supply dirty intermediates. Since home only produces and consumes clean intermediates, no trade will take place, and foreign intermediate and final goods producers will face the laissez-faire (autarky) price. Under this policy regime, we thus have $\tilde{Y}_{dt}^W = \tilde{Y}_{fdt}^{LF}$. Hence, at any point in time, $\tilde{Y}_{dt}^W$ is minimized at $\tilde{Y}_{fdt}^{LF}$ with $p_t^R = p_t^{R,LF}$. □

Lemma 2.A.2. *If A_d is constant, then $Y_d^{W,MIN}$ (weakly) falls over time if and only if $\varepsilon \geq (1-\beta)\,/\,(1-\alpha-\beta)$. If A_d grows over time, then $Y_d^{W,MIN}$ (weakly) falls over time if and only if $\varepsilon > (1-\beta)\,/\,(1-\alpha-\beta)$ and growth in A^R is positive and sufficiently high.*

Proof. By Lemma 2.A.1 and (2.22), minimum global dirty intermediates supply reads

$$Y_{dt}^{W,MIN} = \left(\left(A_t^R\right)^{\frac{\sigma}{1+(\varepsilon-1)\beta}} + 1 \right)^{\frac{1-\beta-\varepsilon(1-\alpha-\beta)}{\sigma}} A_{dt} L_f^{\frac{1-\alpha-\beta}{1-\alpha}} \left(\frac{\alpha}{\psi}\right)^{\frac{\alpha}{1-\alpha}}.$$

$Y_{dt}^{W,MIN}$ is always increasing in A_{dt}. It is increasing in A_t^R if $\varepsilon < (1-\beta)\,/\,(1-\alpha-\beta)$, constant in A_t^R if $\varepsilon = (1-\beta)\,/\,(1-\alpha-\beta)$ and falling in A_t^R if $\varepsilon > (1-\beta)\,/\,(1-\alpha-\beta)$. By (2.25), $A_{jt} \geq A_{jt-1}$ with strict inequality for at least one $j \in \{c, d\}$. So if $A_{dt} = A_{dt-1}$, $A_t^R > A_{dt-1}^R$. Thus, Y_d^{MIN} is constant if $\varepsilon = (1-\beta)\,/\,(1-\alpha-\beta)$ and A_d is constant. If $\varepsilon > (1-\beta)\,/\,(1-\alpha-\beta)$ and A_d is constant, Y_d^{MIN} falls over time. Then by continuity, if A_d grows over time, a $Y_d^{W,MIN}$ that is weakly decreasing over time requires $\varepsilon \geq (1-\beta)\,/\,(1-\alpha-\beta)$ and an A^R that rises sufficiently fast. □

Lemma 2.A.3. *$A_t^R > A_{dt-1}^R$ if and only if $s_{ct}^W > s_{dt}^W$.*

Proof. By (2.25), $A_t^R > A_{t-1}^R$ if

$$A_{t-1}^R \left(\frac{\gamma z s_{ct}^W + 1}{\gamma z s_{dt}^W + 1} \right) > A_{t-1}^R,$$

which is true if and only if $s_{ct}^W > s_{dt}^W$. □

Lemma 2.A.4. *Home can only implement $s_{cv}^W > s_{dv}^W$ for any $v > t$ if it can implement $s_{ct}^W > s_{dt}^W$.*

Proof. There are two ways for home to implement $s_{cv}^W > s_{dv}^W$. First, if $s_h > s_f$, it can use domestic innovation subsidies, q_{hv}, to implement $s_{cv}^W > s_{dv}^W$: By (2.27), for a given the scientist allocation, τ_{hjv} and $\tilde{\tau}_{hjv}$, Π_{hv}^R is increasing in q_{hv}^R. As s_h and s_f are exogenous, if this option is available at time t, it will be available at any time $v > t$. Second, if $s_h \leq s_f$, home needs to redirect foreign scientists to the clean sector to implement $s_{cv}^W > s_{dv}^W$. In the remainder of this proof, we show that home is more likely able to redirect a sufficient number of foreign scientists to the clean sector to implement $s_{ct}^W > s_{dt}^W$ the higher is A_{t-1}^R. From here it follows that if home cannot implement $s_{ct}^W > s_{dt}^W$, we must have $A_t^R \geq A_{t-1}^R$. This in turn implies home cannot implement $s_{cv}^W > s_{dv}^W$ for any $v > t$. Hence, home can only implement $s_{cv}^W > s_{dv}^W$ for any $v > t$ if it can implement $s_{ct}^W > s_{dt}^W$.

When $s_f > s_h$, home implements $s_{ct}^W > s_{dt}^W$ if it implements policies such that $\Pi_{ft}^R = L_{ft}^R \left(\frac{\gamma z s_{ct}^W + 1}{\gamma z s_{dt}^W + 1} \right)^{-1} \geq 1$ for some $Z_t \equiv \frac{\gamma z s_{ct}^W + 1}{\gamma z s_{dt}^W + 1} > 1$, where we use (2.16) and (2.24). Hence we need $L_{ft}^R \geq Z_t > 1$. Then by (2.15) we can rewrite this condition to $p_t^R \geq Z_t^\beta \left(A_t^R \right)^{\alpha - 1}$. This is true if for $p_t^R = Z_t^\beta \left(A_t^R \right)^{\alpha - 1}$, world relative demand for clean intermediates is greater than or equal to relative supply: $Y_{ct}^{WR} \geq \tilde{Y}_{ct}^{WR}$. Now at $p_t^R = Z_t^\beta \left(A_t^R \right)^{\alpha - 1}$, by (2.4), (2.15) and (2.17), we find

$$\tilde{Y}_t^{WR} = \frac{\left(\tilde{\tau}_{ht}^R\right)^{-\frac{1-\beta}{\beta}} \left(p_{wt}^R\right)^{-\frac{\alpha}{1-\alpha}} \frac{1+Z_t}{1+Z_t\left(\tilde{\tau}_{ht}^R\right)^{-\frac{1-\beta}{\beta}}} \left(L_w^R\right)^{\frac{1-\alpha-\beta}{1-\alpha}} X_t + 1}{\left(p_{wt}^R\right)^{-\frac{\alpha}{1-\alpha}} \frac{1+Z_t}{1+Z_t\left(\tilde{\tau}_{ht}^R\right)^{-\frac{1-\beta}{\beta}}} \left(L_w^R\right)^{\frac{1-\alpha-\beta}{1-\alpha}} X_t + 1} \left(A_t^R\right)^{1-\alpha} Z_t^{1-\beta}, \tag{2.A.1}$$

where

$$X_t \equiv \left(\frac{1 + Z_t \left(\tilde{\tau}_{ht}^R\right)^{-\frac{1}{\beta}}}{1 + Z_t} \right)^{-\frac{1-\alpha-\beta}{1-\alpha}} \frac{1 + Z_t \left(\tilde{\tau}_{ht}^R\right)^{-\frac{1-\beta}{\beta}}}{1 + Z_t} \tilde{\tau}_{hdt}^{-\frac{\alpha}{1-\alpha}}, \tag{2.A.2}$$

and we know

$$p_{wt}^R = \left(\tau_{hdt}^{1-\varepsilon} \frac{\left(p_t^R\right)^{1-\varepsilon} \left(\tau_{ht}^R\right)^{1-\varepsilon} + 1}{\left(p_t^R\right)^{1-\varepsilon} + 1} \right)^{\frac{1}{1-\varepsilon}}. \tag{2.A.3}$$

In addition, by (2.10) and (2.16) we can write Y_t^{WR} at $p_t^R = Z_t^\beta \left(A_t^R\right)^{\alpha-1}$ as

$$Y_t^{WR} = \frac{\left(\tau_{ht}^R\right)^{-\varepsilon} \left(p_{wt}^R\right)^{-\frac{\alpha}{1-\alpha}} \frac{1+Z_t^{\beta(1-\varepsilon)}\left(A_t^R\right)^\sigma}{1+Z_t^{\beta(1-\varepsilon)}\left(A_t^R\right)^\sigma \left(\tau_{ht}^R\right)^{-\varepsilon}} \left(L_w^R\right)^{\frac{1-\alpha-\beta}{1-\alpha}} X_t + 1}{\left(p_{wt}^R\right)^{-\frac{\alpha}{1-\alpha}} \frac{1+Z_t^{\beta(1-\varepsilon)}\left(A_t^R\right)^\sigma}{1+Z_t^{\beta(1-\varepsilon)}\left(A_t^R\right)^\sigma \left(\tau_{ht}^R\right)^{-\varepsilon}} \left(L_w^R\right)^{\frac{1-\alpha-\beta}{1-\alpha}} X_t + 1} \left(A_t^R\right)^{\varepsilon(1-\alpha)} Z_t^{-\varepsilon\beta}. \tag{2.A.4}$$

The question we address is under what conditions it is feasible for home to implement $Y_t^{WR} \geq \tilde{Y}_t^{WR}$ for $p_t^R = Z_t^\beta \left(A_t^R\right)^{\alpha-1}$. Here, home has four policy instruments: the levels of the two intermediate output taxes, and the two intermediate input taxes. We first show that, if home aims to maximize the difference between relative demand and supply of the clean intermediate, it will never implement positive taxes on clean intermediate demand and dirty intermediate output. This is intuitive, as a positive clean intermediate demand tax will directly reduce home demand for the clean intermediate, and hence reduce Y_t^{WR}. Similarly, a dirty output tax reduces home supply of the dirty intermediate and thus increases $\tilde{Y}_t^{WR}$. This is presented more formally by the following lemma.

Lemma 2.A.4.1 *To maximize $Y_t^{WR} - \tilde{Y}_t^{WR}$, home must set $\tau_{hct} = \tilde{\tau}_{hdt} = 1$.*

Proof. By (2.A.3), multiple levels of τ_{ht}^R support a given p_{wt}^R. We use this property to show that to maximize $Y_t^{WR} - \tilde{Y}_t^{WR}$, we never have $\tau_{ht}^R > 1$. First, for a given p_{wt}^R, $\tilde{Y}_t^{WR}$ is independent of output taxes τ_{jht} (see 2.A.1), yet Y_t^{WR} is falling in τ_{ht}^R (see 2.A.4). Hence, for a given p_{wt}^R, to maximize $Y_t^{WR} - \tilde{Y}_t^{WR}$, one must minimize τ_{ht}^R. However, to maintain this p_{wt}^R, any reduction in τ_{ht}^R requires an increase in τ_{hdt} and a reduction in τ_{hct}.[35] As we require $\tau_{hjt} \geq 1$, $\tau_{ht}^R > 1$ implies $\tau_{hct} > 1$ and a reduction in τ_{ht}^R while maintaining p_{wt}^R is always feasible. If $\tau_{ht}^R \leq 1$ however, we may have $\tau_{hct} = 1$ (which we will later see is indeed the case), and further reductions in τ_{ht}^R may not be feasible. Thus, we conclude that maximizing $Y_t^{WR} - \tilde{Y}_t^{WR}$ implies $\tau_{ht}^R \leq 1$.

Next by (2.A.2), multiple levels of $\tilde{\tau}_{ht}^R$ support a given X_t. We use this property to show that to maximize $Y_t^{WR} - \tilde{Y}_t^{WR}$, we never have $\tilde{\tau}_{ht}^R < 1$. First, for a given X_t, $\tilde{Y}_t^{WR}$ is falling in $\tilde{\tau}_{ht}^R$ and Y_t^{WR} is independent of X_t. Hence, for a given X_t, to maximize $Y_t^{WR} - \tilde{Y}_t^{WR}$, one must maximize $\tilde{\tau}_{ht}^R$. For $\tilde{\tau}_{ht}^R \geq 1$, to maintain a given X_t, an increase in $\tilde{\tau}_{ht}^R$ requires an fall in $\tilde{\tau}_{hdt}$. Again we require $\tilde{\tau}_{hjt} \geq 1$, so as long as $\tilde{\tau}_{hdt} > 1$, we

[35] More specifically we have $d\tau_{hct}/d\tau_{hdt} = -\left(p_t^R\right)^{\varepsilon-1}\left(\tau_{ht}^R\right)^\varepsilon$.

can increase $\tilde{\tau}_{ht}^{R}$ while maintaining X_t. For some $\tilde{\tau}_{ht}^{R} \ll 1$ however, we find that an increase in $\tilde{\tau}_{ht}^{R}$ requires an increase in $\tilde{\tau}_{hdt}$ and $\tilde{\tau}_{hct}$. This is always feasible. Starting from such an equilibrium, increasing $\tilde{\tau}_{ht}^{R}$ implies we always find ourselves at $\tilde{\tau}_{ht}^{R} \geq 1$ as of some point, where further increases in $\tilde{\tau}_{ht}^{R}$, while keeping X_t constant, requires reducing $\tilde{\tau}_{hdt}$. Hence, we can conclude that maximizing $Y_t^{WR} - \tilde{Y}_t^{WR}$ implies $\tilde{\tau}_{ht}^{R} \geq 1$.

We have now established that the combination of some $\tau_{ht}^{R} \leq 1$ and $\tilde{\tau}_{ht}^{R} \geq 1$ maximizes $Y_t^{WR} - \tilde{Y}_t^{WR}$. Now, given τ_{ht}^{R}, $Y_t^{WR} - \tilde{Y}_t^{WR}$ is maximized by minimizing p_{wt}^{R}. Above, we found that for given τ_{ht}^{R}, p_{wt}^{R} is increasing in τ_{hdt}. Hence, the $\tau_{ht}^{R} \leq 1$ we set must be set such that τ_{hdt} is minimized, which is the case if we set $\tau_{hct} = 1$. Additionally, given $\tilde{\tau}_{ht}^{R}$, $Y_t^{WR} - \tilde{Y}_t^{WR}$ is maximized by maximizing X, where X is falling in $\tilde{\tau}_{hdt}$. Hence, the $\tilde{\tau}_{ht}^{R} \geq 1$ we set must be set such that $\tilde{\tau}_{hdt}$ is minimized, which is the case if we set $\tilde{\tau}_{hdt} = 1$. □

Next using $\tilde{\tau}_{hdt} = \tau_{hct} = 1$, and (2.A.1) and (2.A.4), $Y_t^{WR} \geq \tilde{Y}_t^{WR}$ implies

$$Z_t^{-(1+(\varepsilon-1)\beta)} \geq G_t, \tag{2.A.5}$$

with

$$\begin{aligned} G_t &= G_{1t} * G_{2t}; \qquad (2.A.6)\\ G_{1t} &\equiv \frac{\left(p_{wt}^{R}\right)^{-\frac{\alpha}{1-\alpha}} \frac{1+Z_t^{\beta(1-\varepsilon)}\left(A_t^R\right)^{\sigma}}{1+Z_t^{\beta(1-\varepsilon)}\left(A_t^R\right)^{\sigma}\tau_{hdt}^{\varepsilon}} \left(L_w^R\right)^{\frac{1-\alpha-\beta}{1-\alpha}} X_t + 1}{\tau_{hdt}^{\varepsilon}\left(p_{wt}^{R}\right)^{-\frac{\alpha}{1-\alpha}} \frac{1+Z_t^{\beta(1-\varepsilon)}\left(A_t^R\right)^{\sigma}}{1+Z_t^{\beta(1-\varepsilon)}\left(A_t^R\right)^{\sigma}\tau_{hdt}^{\varepsilon}} \left(L_w^R\right)^{\frac{1-\alpha-\beta}{1-\alpha}} X_t + 1};\\ G_{2t} &\equiv \frac{\tilde{\tau}_{hct}^{-\frac{1-\beta}{\beta}}\left(p_{wt}^{R}\right)^{-\frac{\alpha}{1-\alpha}} \frac{1+Z_t}{1+Z_t\tilde{\tau}_{hct}^{-\frac{1-\beta}{\beta}}} \left(L_w^R\right)^{\frac{1-\alpha-\beta}{1-\alpha}} X_t + 1}{\left(p_{wt}^{R}\right)^{-\frac{\alpha}{1-\alpha}} \frac{1+Z_t}{1+Z_t\tilde{\tau}_{hct}^{-\frac{1-\beta}{\beta}}} \left(L_w^R\right)^{\frac{1-\alpha-\beta}{1-\alpha}} X_t + 1} \left(A_t^R\right)^{-\sigma}. \end{aligned}$$

Then, using $\tilde{\tau}_{hct} \geq 1$ and $\tau_{hdt} \geq 1$, we can show $dG/dA_t^R < 0$. As, for a given Z_t, $dA_t^R/dA_{t-1}^R > 0$, this implies $dG/dA_{t-1}^R < 0$. Hence, the greater A_{t-1}^R, the more likely home can implement equilibrium relative prices p_t^R that exceed the level required to sufficiently increase the production of clean intermediates in the foreign country, and thereby redirect foreign scientists to the clean sector.

Finally, when $s_{ct}^W > s_{dt}^W$, can be implemented, A_t^R growing over time can be implemented. Hence, there exists some finite time T, at which we can achieve $A_{T-1}^R > \min\left\{1, \left(\gamma z s^W + 1\right)^{\frac{1-(\varepsilon-1)(1-\alpha-\beta)}{\sigma}}\right\}$. By (2.26), this implies as of time T, laissez-faire global innovation takes place in the clean sector only. This is a sufficient condition for $s_c^W = s^W$ and $Y_d^W = Y_d^{W,MIN}$ being simultaneously implemantable. Simultaneously, under $s_c^W = s^W$, A_{dt} is constant over time while A_t^R grows. Then, it follows from Lemma 2.A.2, that $\lim_{t\to\infty} Y_{dt}^{W,MIN} \to 0$ (if $\varepsilon < (1-\beta)\,/\,(1-\alpha-\beta)$) or $\lim_{t\to\infty} Y_{dt}^{W,MIN} \to Y^{W,LIM} < \infty$ (if $\varepsilon < (1-\beta)\,/\,(1-\alpha-\beta)$). In turn, this implies that the maximum element in $\mathbf{E_{t^+}}$ is bounded; there exists some $\bar{E} < \infty$ such that home can ensure $E_\nu < \bar{E}$ is satisfied for any ν. □

2.A.2 Proof to Proposition 2.1

By Lemma 2.3, to implement sustainable growth, policy must implement $s_{ct}^W > s_{dt}^W$. If $s_h > s_f$, this requires $\Pi_{ht}^R \geq 1$ for some $s_{ct}^W > s_{dt}^W$. By (2.27), for a given the scientist allocation, τ_{hjt} and $\tilde{\tau}_{hjt}$, Π_{ht}^R is increasing in q_{ht}^R. So a sufficiently high q_{ht}^R will implement $s_{ct}^W > s_{dt}^W$. Next take as given the scientist allocation, τ_{hjt} and q_{hjt}. Now suppose home sets a tax on dirty intermediate production such that $\tilde{\tau}_{ht}^R \to 0$. Then $\Pi_{ht}^R \to \infty$ unless also $p_t^R \to 0$ such that either $p_t^R \left(\tilde{\tau}_{ht}^R\right)^{-1}$ has some positive discrete value, or $p_t^R \left(\tilde{\tau}_{ht}^R\right)^{-1} \to 0$. By (2.15) and (2.16) country k relative supply reads $\tilde{Y}_{kt}^R = \left(p_t^R\right)^{\frac{1-\beta}{\beta}} \left(\tilde{\tau}_{kt}^R\right)^{-\frac{1-\beta}{\beta}} \left(A_t^R\right)^{\frac{1-\alpha}{\beta}}$. Then with $p_t^R \to 0$, $\tilde{Y}_{ft}^R \to 0$ and either $\tilde{Y}_{ht}^R$ has some positive discrete value, or, if $p_t^R \left(\tilde{\tau}_{ht}^R\right)^{-1} \to 0$, $\tilde{Y}_{ht}^R \to 0$. However, by (2.10), if $p_t^R \to 0$, $Y_t^{WR} \to \infty$. Hence, $p_t^R \to 0$ in response to $\tilde{\tau}_{ht}^R \to 0$ cannot be an equilibrium. From here it follows that for $\tilde{\tau}_{ht}^R \to 0$, we must have $\Pi_{ht}^R \to \infty$. By continuity, $\Pi_{ht}^R \geq 1$ can also be implemented for some $\tilde{\tau}_{ht}^R$ strictly larger than zero. □

2.A.3 Proof to Proposition 2.2

By Lemma 2.3, home can only implement a sustainable growth path at time t if $\varepsilon \geq (1-\beta)\,/\,(1-\alpha-\beta)$, $\bar{E}$ is sufficiently high and it can implement $s_{ct}^W > s_{dt}^W$. By Assumption 2.1, absent of environmental policies, $s_{fct} = 0$. So if $s_f > s_h$, home must redirect a sufficient number of foreign scientists to the clean sector to implement $s_{ct}^W > s_{dt}^W$. From the proof to Lemma 2.3 we know that the greater A_{t-1}^R, the more likely home can implement $s_{ct}^W > s_{dt}^W$. In addition, by (2.A.6), $dG_1/dL_w^R \leq 0$ whenever $\tau_{hdt} \geq 1$, with strict inequality if $\tau_{hdt} > 1$. Similarly, $dG_2/dL_w^R \leq 0$ whenever $\tilde{\tau}_{hct} \geq 1$, with strict inequality if $\tilde{\tau}_{hct} > 1$. Note that if $\tilde{\tau}_{hct} = 1$, some $\tau_{hdt} > 1$ must be implemented to reduce global demand for the dirty intermediate and ensure the incentive for foreign scientists to innovate in clean is increased. Similarly, if $\tau_{hdt} = 1$, redirecting foreign scientists requires $\tilde{\tau}_{hct} > 1$. Hence, when home implements sustainable growth, we have $\tilde{\tau}_{hct} > 1$ and/or $\tau_{hdt} > 1$. From here, it then follows that $dG/dL_w^R < 0$. Hence, also the larger is L_h/L_f, the more likely home is able to redirect a sufficient number of foreign scientists to the clean sector such that $s_{ct}^W > s_{dt}^W$. □

2.A.4 Proof to Proposition 2.3

The naive social planner chooses the paths of machine production, x_{kjit}, labor allocation, L_{hct}, and relative intermediates prices, p_t^R that maximize intertemporal utility (2.1) subject to $Y_{kt} = \tilde{Y}_{kt} - \psi\left[\int_0^1 x_{kcit}di + \int_0^1 x_{kdit}di\right]$, (2.2), (2.4), and (2.6) for $k = h$, (2.8) and, by (2.6), $Y_{hjt} = IM_{jt}\left(p_t^R\right) + \tilde{Y}_{hjt}$ where $IM_{jt}(p_t) \equiv \tilde{Y}_{fjt}\left(p_t^R\right) - Y_{fjt}\left(p_t^R\right)$, while taking the path of technology as given. First, define $\lambda_{ht} = \frac{\partial U_{ht}}{\partial Y_{ht}}$ as the shadow value of one unit of final output, and $\lambda_{hjt} = \lambda_{ht}\frac{\partial Y_{ht}}{\partial Y_{hjt}}$ as the shadow value of input j in final output production. Similarly, we take $\lambda_{hEt} = \frac{\partial U_{ht}}{\partial \mathbf{E_{t+}}}\frac{\partial \mathbf{E_{t+}}}{\partial \tilde{Y}_{dt}^W}$ as the shadow value of emissions at time t. Here, we have $\lambda_{ht}, \lambda_{hjt} > 0$ and $\lambda_{hEt} < 0$. The FOC with respect to L_{hct} implies that the social planner allocates labor according to

$$\left(\lambda_{hdt} + \lambda_{hEt}\right)\frac{\partial \tilde{Y}_{hdt}}{\partial L_{hdt}} = \lambda_{hct}\frac{\partial \tilde{Y}_{hct}}{\partial L_{hct}}.$$

The FOC with respect to p_t^R then gives that in the optimum

$$\lambda_{hdt}\frac{\partial IM_{dt}}{\partial p_t^R} + \lambda_{hct}\frac{\partial IM_{ct}}{\partial p_t^R} + \lambda_{hEt}\frac{\partial \tilde{Y}_{fdt}}{\partial p_t^R} = 0. \tag{2.A.7}$$

In the market equilibrium, the final output producer equates the relative return to clean and dirty input use to its marginal cost: $\frac{\partial Y_{ht}/\partial Y_{hct}}{\partial Y_{ht}/\partial Y_{hct}} = p_t^R \tau_{ht}^R$ (see (2.9)) Similarly, by labor mobility, the return to labor is equal across sectors (see (2.13)): $p_{dt}\tilde{\tau}_{hdt}^{-1}\frac{\partial \tilde{Y}_{hdt}}{\partial L_{hdt}} = p_{ct}\tilde{\tau}_{hct}^{-1}\frac{\partial \tilde{Y}_{hct}}{\partial L_{hct}}$. This gives us that in the optimum, we must have $p_t^R\tau_{ht}^R = \frac{\lambda_{hct}}{\lambda_{hdt}}$ and $p_t^R\left(\tilde{\tau}_{ht}^R\right)^{-1} = \frac{\lambda_{hct}}{\lambda_{hdt}+\lambda_{hEt}}$. From here we derive the optimal tax wedge

$$\frac{\lambda_{hdt}}{\lambda_{hdt} + \lambda_{hEt}} = \left(\tilde{\tau}_{ht}^R\tau_{ht}^R\right)^{-1} > 1.$$

The environmental externality calls for a net tax on dirty intermediates output and/or input. The greater the environmental externality, the more negative λ_{hEt} and hence the larger dirty taxes are called for. The optimal use of policy tools depends on foreign's response. By balanced trade, we have $p_t^R IM_{ct} + IM_{dt} = 0$ for any p_t^R, which implies $IM_{ct} + p_t^R\frac{\partial IM_{ct}}{\partial p_t^R} + \frac{\partial IM_{dt}}{\partial p_t^R} = 0$. Using this in addition to the above results, allows us to rewrite (2.A.7) to

$$\tau_{ht}^R\left(\tilde{\tau}_{ht}^R\tau_{ht}^R - 1\right)^{-1}\left(\tilde{\tau}_{ht}^R - \left(1 + \frac{IM_{ct}}{\partial IM_{dt}/\partial p_t^R}\right)\right) + \frac{\partial Y_{fdt}/\partial p_t^R}{\partial IM_{dt}/\partial p_t^R} = 0.$$

From here, we can show that the social planner will never set $p_t^R \geq p_t^{LF}$. From the definition of IM_{dt}, and by $\partial \tilde{Y}_{fdt}/\partial p_t^R < 0$ and $\partial Y_{fdt}/\partial p_t^R > 0$ we know $\frac{\partial Y_{fdt}/\partial p_t^R}{\partial IM_{dt}/\partial p_t^R} \in (-1, 0)$. Then, in the optimum $\tau_{ht}^R \left(\tilde{\tau}_{ht}^R \tau_{ht}^R - 1\right)^{-1} \left(\tilde{\tau}_{ht}^R - \left(1 + \frac{IM_{ct}}{\partial IM_{dt}/\partial p_t^R}\right)\right) < 1$, or $\tau_{ht}^R \left(1 + \frac{IM_{ct}}{\partial IM_{dt}/\partial p_t^R}\right) > 1$. For $p_t^R \geq p_t^{LF}$, we have $IM_{ct} \geq 0$, which by $\partial IM_{dt}/\partial p_t^R < 0$ implies we require $\tau_{ht}^R > 1$. By Lemma 2.1, to set $p_t^R \geq p_t^{LF}$, $T_{ht} = \left(\tau_{ht}^R\right)^{-\frac{\varepsilon}{1-\beta}} \tilde{\tau}_{ht}^R$ must be greater than or equal to unity. With $\tau_{ht}^R > 1$, this implies we need $\tilde{\tau}_{ht}^R > 1$. However, this gives $\tilde{\tau}_{ht}^R \tau_{ht}^R > 1$ which contradicts the requirement on the optimal tax wedge. □

2.B Calibration

2.B.1 Calibration details

In addition to choosing parameter values, we calibrate the ratio of home labor to foreign, L_h/L_f, the ratio of home scientists to foreign, s_h/s_f and the initial ratio of clean technology to foreign A_{c0}/A_{d0}. Finally, we translate the percentage tax rates into tax values.

The L_h/L_f ratio is calibrated as follows. From expression (2.22) we find the following relationship between the (laissez-faire) ratios of output and labor: $L_h/L_f = \left(Y_h/Y_f\right)^{\frac{1-\alpha}{1-\alpha-\beta}}$. This expression is derived based on a two-country structure. In the context where h denotes the set of participating countries and f the set of remaining countries not participating in the climate coalition, we have $L_h/L_f = \left(\sum_{k\in h} Y_k^{\frac{1-\alpha}{1-\alpha-\beta}} / \sum_{k\in f} Y_k^{\frac{1-\alpha}{1-\alpha-\beta}}\right)$. We then take the 2013 GDP data from the World Economic Outlook database (IMF, 2015) to determine all Y_k, which are then used to compute L_h/L_f according to the latter expression. Note that by this calibration we re-interpret labor in efficiency units, i.e., we implicitly allow for cross-country productivity differences that are not biased towards any intermediate.[36]

The s_h/s_f ratio is calibrated directly based on patent counts. Let Q_k be the total patent applications originating from country k, then $s_h/s_f = \left(\sum_{k\in h} Q_k / \sum_{k\in f} Q_k\right)$. We use 2013 patent application data from the WIPO statistics database WIPO (2014).

To calibrate A_{c0}/A_{d0} we follow the approach by Acemoglu et al. (2012) who calibrate A_{c0}/A_{d0} to match the implied (laissez-faire) value of Y_{c0}/Y_{d0} to the ratio of nonfossil to fossil fuel in world primary energy supply. From (2.22), we have

[36] With $\beta > 0$, intermediates production diminishing returns to scale which implies there are efficiency gains for small countries. The effect on computed coalition sizes is, however, small: taking $\beta = 0$ changes the L_h/L_f computed by at most 0.03, and does not affect the area countries are located in in Figure 2.2.

$Y_{ct-1}/Y_{dt-1} = (A_{ct-1}/A_{dt-1})^{\frac{\varepsilon(\alpha-1)}{1+(\varepsilon-1)\beta}}$. According to IEA, in 2013, 18.3 percent of world primary energy supply originated from nonfossil sources (IEA, IEA). This gives $A_{ct-1}/A_{dt-1} = 0.4679$. This calibration approach allows the reader to directly compare our calibration results to Acemoglu et al. (2012). We also believe this is a valid interpretation of Y_c and Y_d because of the following. The burning of fossil fuels for energy use is the primary source of greenhouse gas emissions. Energy in turn, will remain a necessity and, especially taking into account developing countries growing energy needs, global demand is unlikely to fall in the foreseeable future. Energy itself, however, can clearly be generated from noncarbon (wind, solar, hydro, nuclear) and carbon sources (coal, oil, gas), which are strong, but still imperfect substitutes. Then, to prevent rising emissions, a shift towards noncarbon (clean) technologies is key.

To map the percentage tax rates to $/tCO$_2$, two approaches can be used. A 100 percent tax is equal to p_{dt}/ξ, where ξ is ton CO$_2$ per unit of dirty intermediate output. Then we have $\frac{p_d}{\xi} = \frac{p_d Y_d}{pY}\frac{pY}{GDP}\frac{GDP}{M}$ where M/GDP is the CO$_2$ intensity of output, which, in 2011, was equal to 0.37 kg/$GDP (World Bank, 2015). We calibrate A_c/A_d based on fossil fuel shares in the economy. Now, we know that by (2.22) in laissez-faire $\frac{Y_d}{Y} = \left(\left(\frac{A_c}{A_d}\right)^{\frac{\sigma}{1+(\varepsilon-1)\beta}} + 1\right)^{-\frac{\varepsilon}{\varepsilon-1}}$. In addition, we know that in laissez-faire $\frac{p_d}{p} = \left(\left(\frac{A_c}{A_d}\right)^{\frac{\sigma}{1+(\varepsilon-1)\beta}} + 1\right)^{-\frac{1}{1-\varepsilon}}$. Then, we can either interpret Y as final output and thus pY equal to nominal GDP, or interpret Y as energy output, and pY as energy expenditures.[37] These two approaches give a maximum and minimum value for the tax level respectively. The US energy share of GDP has hovered around 8 percent over the past decades (EIA, 2015). Then given our calibrated value of $A_{ct-1}/A_{dt-1} = 0.4679$ and parameter values as described in Section 2.B we find $p_d/\xi \in (\$158/\text{tCO}_2, \$1974/\text{tCO}_2)$.

2.B.2 International property rights protection

In the model, we assume scientists cannot patent their innovation abroad. As a consequence, innovation incentives in foreign are fully determined by foreign machine demand. In this section, we weaken this assumption and allow foreign scientists to also patent their innovation in home and vice versa. More specifically, we redefine expected profits from innovation to

$$\Pi_{kjt} = \mathrm{E}\left[\pi_{kjit} + \chi\pi_{-kjit}\right], \tag{2.B.1}$$

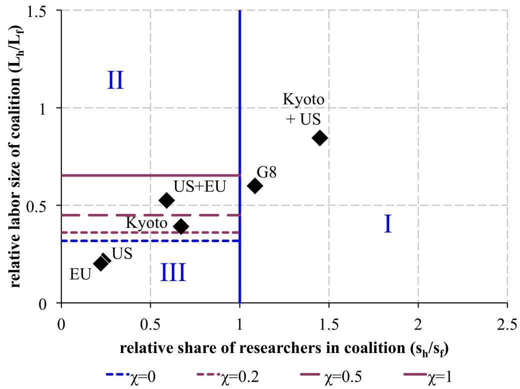
[37] The former approach is adopted by Hourcade et al. (2012).

where E is the expectations operator, $-k$ refers to the country other than k and $\chi \in [0, 1]$ is a measure of international property rights enforcement (IPR), expressed as the share of profits in (2.12) a scientist captures if it sells its patent to a machine producer in the other country. We continue to assume that all unpatented machines will be produced under perfect competition. Figure 2.B.1 then reproduces Figure 2.2 under alternative assumptions for χ. We find that if $s_h < s_f$, the larger χ, the larger the required coalition to implement sustainable growth. Put differently, the easier innovations can be patented abroad, the more difficult it is to redirect foreign scientists the clean sector. This is due to the following. As before, to increase $\mathrm{E}\left[\pi_{fcit}\right]$ relative to $\mathrm{E}\left[\pi_{fdit}\right]$ requires implementing policies that increase the world market price of the clean relative to the dirty intermediate, and thereby move clean intermediates production for foreign. On the flip side, however, this implies that in home, dirty intermediates production rises relative to clean, which translates into an increase of π_{hdit} relative to π_{hcit}. This latter effect mutes the effect of unilateral policies on the foreign scientists' innovation decision, and more so for larger χ. Hence, with a larger χ, larger shifts in production are required to redirect foreign scientists to clean innovation. And such larger shifts can only be implemented by larger coalitions.

Dechezleprêtre et al. (2011) found that on average in 2005, just under 20 percent of patents were patented in a second country. This would correspond to a value of χ of 0.2. With this value, the Kyoto coalition and the coalition of the US and EU can still implement sustainable growth. If χ rises to 0.5, which is the average rate at which developed countries export patents (Dechezleprêtre et al., 2011), the Kyoto coalition is no longer large enough to implement sustainable growth. If all innovations are patented internationally, i.e., if $\chi = 1$, we find that neither the Kyoto coalition, nor a coalition of the US and EU are large enough to redirect scientists outside the coalition to clean innovation.

Under $\chi = 0$, to redirect foreign scientists to the clean sector, home had to implement policies that redirect clean production to foreign and turn home in to a dirty intermediate exporter. Under $\chi > 0$, alternative allocations of production may now also be effective in redirecting foreign scientists to the clean sector. If home significantly increases its own demand for clean machines this may be a sufficient incentive for the foreign innovator to refocus innovation to the clean sector, even if in foreign, profits from clean machines are low relative to dirty machines. Hence, policies that turn home into a dirty intermediate exporter may implement a sustainable growth path even if foreign inhabits the majority of scientists. Nevertheless, when putting some numbers to the story, we find that this is not easy. In fact, for $\chi = 1$, we need L_h/L_f to exceed 2.3 for such a strategy to be effective. In the real world, one would expect that such a coalition, where the effective labor force of the insiders is more

Figure 2.B.1: Coalitions that can (I and II) and cannot (III) implement sustainable growth under alternative assumptions for χ



than twice as large as the outsider labor force, also has greater innovative power, i.e., $s_h > s_f$. We would then again find ourselves in Area I and simply redirecting domestic scientists is sufficient to implement sustainable growth.

The international protection of dirty patents undermines the effectiveness of unilateral policies in redirecting foreign scientists to the clean sector. This raises the question whether a policy of protecting only clean patents from foreign could be fruitful instead.[38] The answer is both yes and no. Selective IPR allows home to redirect foreign innovators with less aggressive tax policies. For instance, in the absence of any input of output taxes, home can redirect foreign scientists by offering full patent protection for clean innovation alone if $L_h/L_f > 1.7$.[39] Yet, selective IPR hardly alters the minimum L_h/L_f required to redirect foreign innovation. This can be explained with the aid of Figure 2.3 in the main text, which shows minimum tax rates to redirect foreign innovators. With L_h/L_f near its 'minimum' of 0.32, clean output and dirty input taxes are very high. In fact, these taxes are so high that they virtually eliminate clean intermediate production in home. With almost zero demand for clean machines in home, introducing clean patent protection no longer contributes to incentivizing foreign scientists to innovate in the clean sector.

[38] I thank an anonymous reviewer for raising this point.
[39] In the context of (2.B.1) this would imply $\chi = 1$ for $j = c$, while $\chi = 0$ for $j = d$

Chapter 3

DOES A RECESSION CALL FOR LESS STRINGENT ENVIRONMENTAL POLICY? A PARTIAL-EQUILIBRIUM SECOND-BEST ANALYSIS

Abstract

This chapter analyzes second-best optimal environmental policy responses to real and financial shocks in a two-period partial equilibrium model with heterogeneous firms, an environmental externality, and credit constraints. We show that, to alleviate credit constraints and encourage investment, the second-best optimal emission tax falls short of marginal emission damages. The optimal response to shocks depends on how the shock affects the size of the environmental and credit market failures and the effectiveness of the tax in alleviating these market failures. Under mildly restrictive assumptions on functional forms, the optimal response to a (persistent) negative productivity shock or a tightening of credit is to reduce the emission tax. Our results are informative for how climate change policy should optimally change with the business cycle.

This chapter is based on joint work with Sjak Smulders

3.1 Introduction

On the 10th of December, 2007, the IPCC and Al Gore received the Nobel Peace Prize for "their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change" (Nobelprize.org, 2007). That same year, the IPCC's Fourth Assessment Report was released, expressing grave concern regarding climate change and the speed at which it is occurring. With the Fifth Assessment Report published recently, and GHG emissions from especially the developing world rising rapidly, the call for policy action has become even stronger since. Nine months after the 2007 Nobel Award Ceremony, Lehman Brothers filed for bankruptcy, triggering the largest global financial crisis since the Great Depression. US GDP fell by more than 3% in 2009, and by 2010, unemployment had risen to almost 10%.

The economic downturn and call for climate action inspired a large policy debate regarding the desirability of implementing, or further strengthening, environmental policies while the economy is in a recession. Some see the economic downturn as an opportunity for climate actions. Inspired by Roosevelt's New Deal, proposals were put forward for a so-called 'Green New Deal'. These proposals consisted of fiscal policy actions benefiting both the economy and the environment. Examples of such actions are the weatherization of homes, investments in green R&D and tax credits for hybrid vehicles. Such a deal would take advantage of the low opportunity cost and high benefits of expansionary fiscal policy in the downturn, while simultaneously benefiting the environment in the long run (UNEP, 2009; Bowen and Stern, 2010; Houser et al., 2009). The recession also proved a threat to the implementation of environmental policy measures. In 2009, the introduction of an Australian carbon trading scheme was delayed due to concerns that it would undermine the economy's recovery (Guardian, 2009). Similar concerns were raised in California, where in 2010 a proposal was put forward to suspend its climate bill until unemployment fell below 5.5% (Wall Street Journal, 2010). The proposal was not approved, but such examples are not stand-alone: Jacobsen (2013) found a significant negative correlation between unemployment rates and US Senate support for environmentally favorable policies.

This chapter contributes to this debate. We formally evaluate the optimal response of environmental policy to those economic shocks that are typically at the root of a recession. We put forward a partial equilibrium model with heterogeneous firms. Energy use causes emissions of harmful pollutants and firms can reduce these emissions by investing in emission-saving technologies. They however face credit constraints, which may limit their ability to invest. More stringent environmental policies, in the form of higher emission taxes, reduce firm profits. Since profits determine borrowing capacity this further tightens credit constraints.

Realistically assuming that the policymaker cannot directly address the credit market imperfections, we characterize the constrained-optimal, or second-best, policy. We find that as long as some firms face binding constraints, the second-best optimal tax falls below marginal damages and varies systematically with the two main shocks that cause recessions, namely a credit shock and a productivity shock. The optimal policy trades off the tax effects on emissions and investment. Since a recession-driving shock changes the relative effect of a tax on firm profits, emissions reduction, and the cost of emission-saving technologies, the optimal tax policy varies with the shock. Our main question is under which conditions the environmental policy should be more stringent in response to recession-related shocks.

Assuming marginal environmental damages are independent of the shock, we identify four different mechanisms through which productivity and credit shocks affect the optimal tax. The first mechanism is the investment value effect. Improved productivity or access to credit allows constrained firms to invest more, which reduces the underinvestment problem. As a result, following a positive one-period shock to credit or productivity, the tax should be refocused towards internalizing environmental externalities, rather than alleviating the financing problem. This makes the tax pro-cyclical. If however, the economy faces a favorable productivity shock that is persistent, the benefits of investment in emission savings also rise, calling for a lower tax. This second, negative effect is the persistence effect. The optimal tax does not only depend on the marginal benefit of increasing investment or reducing emissions, but also on the degree to which (a change in) the tax affects investment and emissions to begin with. For example, if constrained firms' investment hardly responds to tax changes, whereas emissions are highly sensitive to the tax, a relatively high tax is optimal. The tax is then relatively effective in reducing emissions, but ineffective in encouraging (or rather discouraging) investment. This identifies the third and the fourth mechanism: the investment and emission sensitivity effect. The former determines the degree to which the shock enhances, or worsens, the effectiveness of tax reductions in alleviating the credit constraint. Similarly, the emission sensitivity effect accounts for the change in the tax' effectiveness in reducing emissions. In our general model, the investment and emissions sensitivity effects are ambiguous and also the sign of the combined effects of the four mechanisms cannot be determined. Under some plausible mildly restrictive assumptions on functional forms we find that the optimal emission tax is pro-cyclical: in a recession, investment is less sensitive to the tax, but since credit constraints are more binding and also emission reductions are harder to achieve, a tax reduction is the best response.

This chapter contributes to a small literature on business cycles and environmental policy that has emerged in recent years.[1] Most work focuses on the optimality of emission taxes versus quota or intensity targets in the presence of economic shocks (Angelopoulos et al., 2010; Dissou and Karnizova, 2012; Fischer and Springborn, 2011). For our chapter, the work by Heutel (2012) is most relevant. Heutel (2012) uses a real business cycle model with a climate externality to determine the optimal environmental policy response to a persistent productivity shock. The cyclicality of the optimal emission tax is governed by two counteracting forces. In booms, output and damages, which are modeled as a share of output, are high. Consumption is high too, which implies the marginal utility of consumption, or the utility value of given damages, is low. Taken together, his calibration reveals the optimal carbon tax is pro-cyclical. Our research question is similar, yet we focus on credit constraints as the main driver of policy cyclicality, abstracting from consumption smoothing effects. Financial sector shocks and lack of access to credit have been a major factor in the recent US recession. Hence, they feature prominently in the rapidly growing macroeconomic literature studying the effects of economic shocks.[2] Also in the theoretical growth literature (Aghion et al., 2010) and subsequent empirical work (Aghion et al., 2012, 2014) point at the importance of credit constraints in the evaluation of the effect of recessions on investment and economic growth. Due to credit constraints, which become especially pressing in recessions, firms may be unable to invest, offering a rationale for cyclical (fiscal) policy aimed at alleviating credit constraints.

The chapter proceeds as follows. Section 3.2 introduces the model. Section 3.3 solves for the equilibrium for given taxes and Section 3.4 for the optimal emission tax. Section 3.5 discusses economic shocks, and the optimal response of the emission tax to these shocks. The model is solved for a specific functional form in Section 3.6. Several assumptions and potential extensions are discussed in Section 3.7, and Section 3.8 concludes. Appendix 3.A discusses optimal emission tax policy under an alternative tax recycling scheme and Appendix 3.B presents an overview of the notation and signs of derivatives.

[1] See Fischer and Heutel (2013).

[2] See for instance Gertler and Kiyotaki (2010), Bassetto et al. (2015) and Khan and Thomas (2013) for evaluations of the effect of economic shocks in a model with credit market imperfections and heterogeneous firms. Earlier references include Bernanke and Gertler (1989), Kiyotaki and Moore (1997) and Bernanke et al. (1999).

3.2 The model

We use a two-period partial-equilibrium model with a continuum of heterogeneous profit-maximizing firms, indexed $i \in [0,1]$. For the purpose of our analysis, the period length need not be defined. Throughout the chapter, we use lowercase letters to denote first-period variables and uppercase letters for second-period variables, subscripts denote partial derivatives. Each firm has access to a common technology y, with a common productivity parameter a, which transforms energy, e, into output:

$$y(a, e(i)) = h(a) f(e(i)), \tag{3.1}$$

where $h' > 0$, $f' > 0$, and $f'' < 0$. Second period output, $Y(A, E(i))$, has exactly the same properties.

Firms are characterized by emission efficiency $z(i) \in [\underline{z}, \overline{z}]$, with $\underline{z} > 0$. We assume a continuous distribution of $z(i)$ over the support, where firms are ranked in ascending order according to $z(i)$: $z'(i) > 0$.[3] We interpret this $z(i)$ as the abatement technology that the firm has adopted and installed prior to the beginning of the first period. In particular, firm i's emissions, $m(i)$, per unit of energy, $e(i)$, equal $1/z(i)$, emissions are given by $m(i) = e(i)/z(i)$.

Emissions impose a negative externality: each unit of emission inflicts a cost Δ on society. To correct for this externality a government may levy an emission tax, t. With a positive t, the heterogeneity in $z(i)$ translates into a heterogeneity in the marginal cost of energy use: $q + t/z(i)$, where q is the cost of energy, supplied by fully competitive firms. Then, firms i's operating profits equal

$$\pi(i) = y(a, e(i)) - (q + t/z(i))\, e(i) - \phi, \tag{3.2}$$

where $\phi \geq 0$ is the fixed production cost and the price of a unit of output is normalized to unity. Again the equation can be repeated in capital letters to represent second period operating profits Π. We abstract from entry, and to ensure all firms are active, we assume the minimal $z(i)$, $\underline{z}$, is such that $\pi(i) > 0$ for all firms.

The firm can invest in abatement technology so that in the second period emission per unit of energy are lower than in the first period, $Z(i) > z(i)$. For short we refer to second-period efficiency Z as investment since given z, a higher level of Z means more investment. In general, to reach a particular efficiency level $Z(i)$ in the second period, starting from $z(i)$ in the first period, the investment cost incurred in

[3] The inequality condition, which implies each firm i has a unique z, facilitates the exposition of results. All results generalize to $z'(i) \geq 0$, or discontinuous distributions.

the first period is

$$C\left(z(i), Z(i)\right), \tag{3.3}$$

with $C_z \leq 0$, $C_Z > 0$, $C_{ZZ} > 0$ and $\lim_{Z \to 0} C \leq 0$. Investment cost are higher the higher the improvement in efficiency over time. An initially high efficiency level may reduce the average and marginal cost of obtaining a given Z. This can be interpreted as convex adjustment costs.

Investments are financed out of retained earnings and bank loans. Bank lending is not unlimited: firms can only borrow a multiple $(\xi - 1)$ of their first-period profits π. This gives the following constraint:

$$C\left(z(i), Z(i)\right) \leq \xi \pi(i), \tag{3.4}$$

where the leverage parameter exceeds one, $\xi \geq 1$.[4] With $\xi \to \infty$, credit constraints are absent and firms can borrow funds without limit. Any retained earnings not used for investment purposes can be deposited at the bank. We abstract from other financial market failures and assume the return received on deposits equals the interest rate on loans.

The timing is as follows. In the first period, first $z(i)$, a, and ξ are observed. Then the regulator sets the tax t, firms choose emissions e, produce, and pay for the pollution tax. Next, firms invest to choose $Z(i)$ and pay for the investment cost, based on rational expectations of future productivity and tax rates. Finally the regulator returns tax revenue either to firms in a lump-sum fashion or to other agents in the economy. Our assumption for now is that any tax revenues are recycled lump-sum and this lump-sum cannot be used for investment purposes, i.e. it does not affect the firms' credit constraints. We postpone discussing the alternative case in which tax recycling alleviates credit constraints; this case is more complex but gives qualitatively the same results.[5] In the second period, firms operate at efficiency level $Z(i)$. Firms and regulator first observe productivity level A, then the regulator sets tax T, and finally firms choose emissions E.

3.3 Equilibrium investment and emissions

In this section we characterize firms' investment and emission decisions as a function of taxes, leverage, productivity, and (first-period) efficiency. To save on notation, we

[4]The credit constraint is equivalent to those adopted in Bassetto et al. (2015) and Khan and Thomas (2013), and an approximation of the endogenous constraints derived in for example Bernanke and Gertler (1989).

[5]We present the full solution of the alternative case in Appendix 3.A, and also provide a short discussion of this case in Section 3.7.

express all variables in present value terms and suppress the firm identifier, i, when no confusion arises. Each firm maximizes the present value of profits subject to the credit constraint by choosing first and second-period energy, e and E, respectively, and second-period emission efficiency, Z:

$$\max_{e,E,Z} \pi + \Pi - C$$
$$\text{subject to } C \leq \xi\pi.$$

only affects profits within the same period, it is a static decision governed by the usual first-order condition:

$$\pi_e = 0 \text{ and } \Pi_E = 0. \tag{3.5}$$

This allows us to write equilibrium energy use as a function of efficiency, productivity, and the tax rate: $e(z(i), t, a)$ and $E(Z(i), T, A)$ for first and second period, respectively.[6] Similarly, emissions m and profits π become functions of the same arguments. The choice of investment follows from the other first-order condition:

$$\Pi_Z = C_Z, \tag{3.6}$$

if $C \leq \xi\pi$, i.e. if the constraint is nonbinding. If however, for the Z implied by (3.6), $C > \xi\pi$, the credit constraint is binding, Z is determined by $C = \xi\pi$ and we have $\Pi_Z > C_Z$ instead.

Equations (3.2) and (3.5) allow us to evaluate the effect of the tax rate and efficiency on energy use and profits.[7] For taxes we find $e_t < 0$ and $\pi_t < 0$: energy use and profits are falling in the tax rate. As long as $t > 0$, the heterogeneity in emission efficiency, z, translates into heterogeneity in energy use and profits across firms. A high z firm has a lower marginal cost of energy use, chooses to use more energy, and obtains higher profits as a consequence. The marginal effect of a change in z on emissions is not directly obvious, however. On the one hand, given energy use, a high emission efficiency implies emissions are low. On the other hand, energy use is increasing in emission efficiency ($e_z > 0$).[8] We restrict attention to the most intuitive

[6] Since we already wrote e as a function of i above, this is a slight abuse of notation, but no confusion between the two functions will arise. Subscripts to the function symbols e and E will uniquely refer to derivatives of the functions just introduced.

[7] For the sake of brevity, we only refer to the derivatives of the first period. All relationships carry over to the second period variables (e.g. if $e_t < 0$, also $E_T < 0$). An overview of all notation and derivatives can be found in Appendix 3.B.

[8] This effect is also known as the energy rebound effect. Over the past years, a literature has emerged that explores under what conditions improvements in green technology reduces harmful emissions, and in what cases stricter environmental policy leads to green technology adoption to begin with. See for example Gil-Molto and Dijkstra (2011), Bréchet and Meunier (2014), Gans (2012), Perino and Requate (2012), Smulders and Di Maria (2012) and also Gillingham et al. (2016).

case by assuming that improvements in green technology reduce harmful emissions:

Assumption 3.1. m_z, $M_Z < 0$

Remark 3.1. If energy demand is sufficiently inelastic, Assumption 3.1 is justified. Intuitively, better abatement technology reduces emissions for given energy use. It also reduces the effective price of energy, $q + t/z$, increases energy demand, and thus tends to increase emissions. The former effects dominates as long as energy demand responds little to price changes. To see this more formally, we note from (3.5) and $m = e/z$ that $m_z = (-y_{ee}z^2)^{-1}[t/z + y_{ee}e]$. Again using (3.5) we can write this as $m_z = \frac{1}{(-y_{ee}z^2)}[\frac{t}{z} + \frac{y_{ee}e}{y_e}(\frac{t}{z} + q)] = \frac{qe}{z^3 y_e}\left[\frac{t}{q}\left(\frac{y_e}{-y_{ee}e} - 1\right) - z\right]$. It follows immediately that $m_z < 0$ requires $z > \frac{t}{q}\left(\frac{y_e}{-y_{ee}e} - 1\right)$. The expression $y_e/(-y_{ee}e)$ is the (positively defined) price elasticity of energy demand; if it is smaller than one, $m_z < 0$ and $M_Z < 0$ for all firms. With more elastic demand, $m_z < 0$ requires a lower bound on z. Similarly, $M_Z < 0$ requires a lower bound on Z, which is determined within the model; a sufficiently flat (marginal) cost curve (C_Z and C_{ZZ} small) will ensure that the endogenously generated level of Z exceeds the lower bound for all firms.

Two observations then follow from Assumption 3.1. First, lower z firms do not only have lower energy use and profits, but also higher emissions.[9] Second, we can show that for unconstrained firms, $Z_T > 0$:[10] stricter environmental policy leads to more green technology investment in the optimum. This is intuitive, but not trivial. For given energy use, the increase in second-period profits due to an increase in Z is higher if taxes are high, as emissions are more costly in that case. However, energy use is lower to begin with when taxes are high, reducing the benefits of investing in emission efficiency Z. As long as Assumption 3.1 is satisfied, the former effect dominates the latter.

Note that the second observation only applies for unconstrained firms. If firms face binding credit constraints, Z follows from (3.4), and is independent of the second-period tax T. For a more elaborate assessment of the choice of Z, we first define the following

Definition 3.1. Let Z^R be the maximal (restricted) choice of Z, and Z^U the optimal (unrestricted) choice of Z. Then, for each firm i, Z^R is implicitly determined through

[9] From (3.2) and (3.5), we derive $e_z = t/(-y_{ee}z^2) > 0$ and $\pi_z = te/z^2 > 0$.

[10] We can show that under Assumption 3.1 $Z_T^U > 0$. First, let $E = \check{E}(\tilde{T})$ with $\tilde{T} \equiv T/Z$ solve (3.5). Since $M = E/Z$, we find $M_T = \check{E}_{\tilde{T}}/Z^2$ and $M_Z = -(T/Z)\check{E}_{\tilde{T}}/Z^2 - M/Z = -(M_T T + M)/Z$. Second, from (3.2) and (3.5), we find $\Pi_Z = MT/Z > 0$, $\Pi_{ZT} = (M + TM_T)/Z$, and $\Pi_{ZZ} = (TM_Z - \Pi_Z)/Z < 0$. Finally, from (3.6) we find $Z_T^U = -\Pi_{ZT}/(\Pi_{ZZ} - C_{ZZ})$. Combining results, we find $Z_T^U = -M_Z/(C_{ZZ} - \Pi_{ZZ}) > 0$.

(3.4) and Z^U through (3.6). If, for firm i, $Z^R < Z^U$, firm i is constrained, while if $Z^R \geq Z^U$, we refer to firm i as unconstrained.

Lemma 3.1. *Maximal second-period emission efficiency is characterized by the function* $Z^R(z(i), t, a, \xi)$ *with* $Z^R_z > 0$, $Z^R_a > 0$, $Z^R_t = -m\xi/C_Z < 0$, *and* $Z^R_\xi = C/C_Z\xi > 0$; *optimal second-period emission efficiency is characterized by the function* $Z^U(z(i), T, A)$ *with* $Z^U_z \geq 0$, $Z^U_A > 0$, *and* $Z^U_T > 0$.

Proof. The derivatives for Z^R and Z^U follow from total differentiation of (3.4) and (3.6), respectively. □

The lemma shows that maximal and optimal efficiency in the second period are non-negatively related with efficiency in the first period. We will use this property to sort firms with different initial efficiency z into constrained and unconstrained firms. Unless $C_z = 0$, both the maximal and optimal efficiency increase with z, since higher efficiency improves profits and alleviates credit constraints as well as reduces investment costs. Because both maximal and optimal investment rise with z, it is not directly obvious whether the low z or the high z firms are more likely constrained. Motivated by a literature that points out that firms need time to 'outgrow' their constraints,[11] we ensure that the smaller firms are constrained. This requires the assumption that the marginal investment cost rise relatively steeply with Z, so that profits rise faster with firm size than desired investment. We first define firm types and then give a sufficient condition under which small firms only are credit constrained.

Definition 3.2. Let $\hat{z}$ be the first-period efficiency such that a firm i with $z(i) = \hat{z}$ is indifferent between maximal and (unconstrained) optimal investment, i.e. $Z^R(\hat{z}, t, a, \xi) = Z^U(\hat{z}, T, A)$.

Assumption 3.2. $C_{Zz} = 0$ or $\frac{C_{Zz}Z}{C_z} \leq \frac{C_{ZZ}Z}{C_Z} + 1$.

Lemma 3.2. *Under Assumption 3.2,* $\hat{z}$ *is unique, and firms with* $z(i) < \hat{z}$ *are credit constrained while firms with* $z(i) \geq \hat{z}$ *are unconstrained.*

Proof. First, we use (3.6) to establish $Z^U_z = [\Pi_{ZZ} - C_{ZZ}]^{-1} C_{Zz}$. From (3.2) and (3.5) we derive $\Pi_Z = TZ^{-2}E = (T/Z)M$, which gives $\Pi_{ZZ} = Z^{-1}[TM_Z - \Pi_Z]$. For an unconstrained firm, $\Pi_Z = C_Z$, so that $\Pi_{ZZ} = Z^{-1}[TM_Z - C_Z]$. Combining results, we find the sensitivity of Z^U to z: $Z^U_z = \frac{-C_{Zz}Z}{ZC_{ZZ}+C_Z-TM_Z}$. Second, we use (3.4) to establish $Z^R_z = C_Z^{-1}[\xi\pi_z - C_z]$. Whenever $C_{Zz} = 0$, we can immediately establish

[11] See for instance Bassetto et al. (2015), Buera and Shin (2013) and Khan and Thomas (2013)

that Z^R increases faster with z than Z^U, since $Z_z^R > Z_z^U$. If $C_{Zz} > 0$, $Z_z^U < 0$, and thus $Z_z^R > Z_z^U$. Finally if $C_{Zz} < 0$, we need to establish that $Z_z^R = \frac{\xi \pi_z - C_z}{C_Z} > \frac{-C_{Zz}Z}{ZC_{ZZ}+C_Z-TM_Z} = Z_z^U \Leftrightarrow \frac{\xi\pi_z}{(-C_z)} + 1 > \frac{C_{Zz}Z/C_z}{ZC_{ZZ}/C_Z+1+(-M_Z)T/C_Z}$. Since $\xi\pi_z/(-C_z) > 0$ and $(-M_Z)T/C_Z > 0$, Assumption 3.2 ensures that the inequality holds. As long as z is unrestricted, this implies that Z^R always cuts Z^U from below. Because of continuity there can be only one crossing. □

Remark 3.2. Many different specifications for the investment cost function (3.3) satisfy Assumption 3.2. A first example is a specification in which the investment cost is independent of first-period efficiency so that $C_z = 0$ and $C_{zZ} = 0$. A second example is the textbook adjustment cost function (cf Romer, 2006), in which z and Z are interpreted as capital stocks in the first and second period respectively, with cost convex in the change in the capital stock, $Z - z$:

$$C(z, Z) = (Z - z) + \frac{\psi}{\eta}(|Z - z|)^{\eta}, \tag{3.7}$$

where $\psi > 0$ and $\eta > 1$. As can be easily checked, this specification implies $C_z < 0$ and Assumption 3.2 is satisfied. A third specification that satisfies the assumption is $C(z, Z) = (Z/z)^{\gamma}$ with $\gamma > 1$.

As a final step we determine the share of constrained firms. To do so, we have to consider that the $\hat{z}$ defined above may fall outside the support for z: $[\underline{z}, \overline{z}]$.

Corollary 3.1. *Let n be the share of constrained firms, such that firms $i \in [0, n)$ are credit constrained while firms $i \in [n, 1]$ are unconstrained. Then, if $\hat{z} < \underline{z}$, $n = 0$. If $\hat{z} > \overline{z}$, then $n = 1$. Finally if $\hat{z} \in [\underline{z}, \overline{z}]$, $z(i) = \hat{z}$, for $i = n$.*

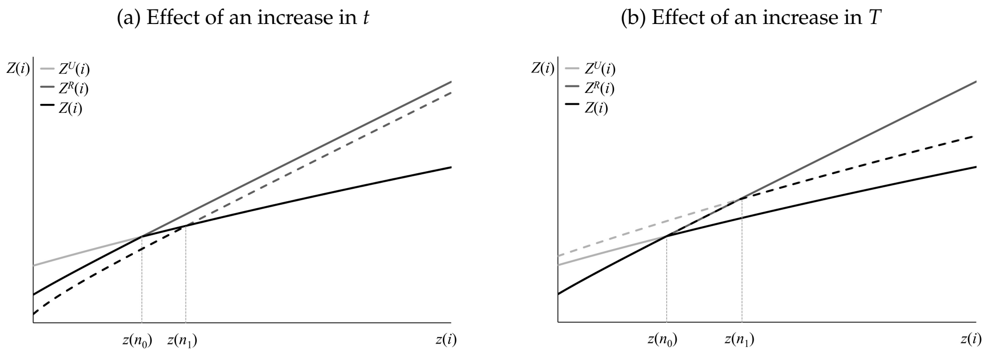
Figure 3.1a and 3.1b illustrate the firms' investment decision and the effect of emission taxes on these decisions. Both figures depict, for different initial levels of efficiency z, the optimal second-period emission efficiency (Z^U, light grey curve) and its maximal, credit-constrained, level (Z^R, dark grey curve). Now assume that $\hat{z} \in [\underline{z}, \overline{z}]$. Then the crossing of the two curves identifies the share of constrained firms, n.[12] The lower envelope (black curve) represents equilibrium Z. For firms with an initial emission efficiency below $z(n)$, the optimal second-period emission efficiency exceeds the maximal choice of Z; these firms are constrained, and thus choose $Z = Z^R$. Both maximal and optimal Z increase with initial level. For $z(i) > z(n)$, the dark grey curve lies above the light grey curve and firms will be able to invest optimally.

[12]Note that whenever the solution is interior, n is not only the share of constrained firms, but also the index of the smallest unconstrained firm.

Figure 3.1a shows the effect of an increase in the first-period tax rate, t, on investment. In this figure, the dashed curves correspond to the higher tax rate. An increase in t reduces first-period profits for all firms. This tightens the credit constraint, reducing Z^R for all firms ($Z_t^R < 0$). The optimal level of Z is independent of t, so the increase in t leaves Z^U unaffected. All in all, we find that an increase in t reduces the second-period emission efficiency of constrained firms, and increases the share of firms that are constrained from n_0 to n_1.

Figure 3.1b shows the effect of an increase in the second-period tax, T, on investment. An increase in the future tax rate increases the cost of emissions, and thereby the return to investment in abatement technology.[13] Hence, it increases optimal second-period emission efficiency, Z^U. With Z^R unchanged however, not all firms will be able to raise sufficient funds to finance the (full) additional investment. While the increase in the second-period tax raises investment by all (previously) unconstrained firms, the number of constrained firms will increase.

Figure 3.1: $Z(i)$ as a function of $z(i)$



Solid lines represent the relationship prior to the tax increase, dashed lines after the tax increase.

The comparative statics exercise above already illustrates the double trade-off a regulator faces when setting the tax. A high tax in the first period reduces not only energy use and emissions, but also output and profits. In addition, as Figure 3.1a shows, it reduces investment by constrained firms, and may increase the number of constrained firms. Less investment in Z implies that emissions will be higher in the second period. In the next section, we will formally analyze this tradeoff and determine optimal policy.

[13]To be more precise, the marginal return to investing in Z reads $\Pi_Z = TEZ^{-1}$. For given E, an increase in T increases Π_Z. However $E_T < 0$: additionally, an increase in T reduces firm energy use, which reduces Π_Z. As long as Assumption 3.1 applies we can show the former effect dominates, so $\Pi_{ZT} > 0$.

3.4 Optimal environmental policy

The regulator sets emission taxes to maximize the discounted sum of firm value added, net of environmental damages. We assume the regulator cannot condition policy on the firm's technology for reasons of information asymmetries, monitoring costs, or equity concerns and political reasons; she is therefore unable to levy firm-specific emission taxes or investment subsidies. We also assume that the regulator cannot commit to a future tax level. As the regulator sets the taxes t and T after firms have made their investment decisions, we can write the regulator's maximization problem as the following two-stage problem:

$$\begin{gathered}\max_t \int_0^1 [\pi + s - \Delta m]\, di + V, \\ V = \max_T \left\{ \int_0^1 [\Pi - C + S - \Delta M]\, di \right\}, \\ \text{subject to (3.5) and (3.6) for } i \in [n,1], \text{ and (3.4) for } i \in [0,n),\end{gathered} \tag{3.8}$$

where s and S are the first- and second-period lump-sum tax rebates and Δ is the exogenous marginal damage from emissions.[14,15] Without loss of generality we assume marginal damages are the same in both periods. We first solve for the optimal second-period tax, T^*. The regulator takes the first-order condition with respect to T, after observing Z, which implies:

$$(\Delta - T^*) \int_0^1 \frac{E_T}{Z} di = 0, \tag{3.9}$$

where T^* is the second-period optimal emission tax; we used (3.5), (3.6), and $S = T \int_0^1 EZ^{-1} di$. This first-order condition directly implies that the optimal second-period tax equals marginal damages, $T^* = \Delta$. In the second period, the environmental externality is the only market failure, and obviously the tax should be set at the Pigouvian level.[16]

Credit constraints, and the second-best nature of the emission tax t, do show up

[14]This assumption concerning Δ is further discussed in Section 3.7.

[15]Note that maximizing the discounted sum of firm value added, net of environmental damages is equivalent to minimizing the sum of firm abatement cost and environmental damages, which is the standard social planner optimization problem in a partial equilibrium framework (see for instance Requate and Unold (2003)). More specifically, let π' and Π' be a firm's first and second-period profits in the absence of environmental policy, respectively. Abatement cost then equal $(\pi' - \pi) + (\Pi' - \Pi) + C$ and the two-stage problem reads $\min_t \int_0^1 [(\pi' - \pi) - s + \Delta m]\, di + V$ subject to (3.5) and (3.6) for $i \geq n$, and (3.4) for $i < n$, where $V = \min_T \left\{ \int_0^1 [(\Pi' - \Pi) + C - S + \Delta M]\, di \right\}$. As the π' and Π' are independent of taxes, z or Z, this problem is equivalent to (3.8).

[16]As explained, we solve for T under the assumption that the regulator cannot commit to T before firms invest. One can however show that the result $T^* = \Delta$ extends to the case where the regulator would be able to commit.

in the first order condition for the first-period tax:

$$(\Delta - t^*) \int_0^1 \frac{e_t}{z} di = \int_0^n [\Pi_Z - C_Z] Z_t^R di + \int_n^1 [\Pi_Z - C_Z] Z_t^U di$$
$$+ \left[\left[\Pi(Z^R(z(n), \cdot) - C(Z^R(z(n), \cdot)) \right] - \left[\Pi(Z^U(z(n), \cdot)) - C(Z^U(z(n), \cdot)) \right] \right] n_t.$$

By Definition 3.2 and Corollary 3.1 we know that either (i) n is the firm that is indifferent between maximal and optimal investment, in which case we have $Z^R(z(n), \cdot) = Z^U(z(n), \cdot)$, or (ii) $n = \{0, 1\}$ and $n_t = 0$. Together with $Z_t^U = 0$ this allows us to reduce the above expression to

$$(\Delta - t^*) \int_0^1 \frac{e_t}{z} di = \int_0^n [\Pi_Z - C_Z] Z_t^R di, \tag{3.10}$$

where t^* is the first-period optimal emission tax. Here we can establish the following

Proposition 3.1. *As long as some firms are constrained, the optimal first-period tax falls short of the Pigouvian tax ($t^* < \Delta$).*

Proof. Since constrained firms invest suboptimally, $\Pi_Z - C_Z > 0$ and $C = \xi\pi$ for firms $i \in [0, n]$. From $C_Z > 0$ and $\pi_t < 0$, the latter implies $Z_t^R < 0$. The result is that the RHS of (3.10) is negative. Together with $e_t < 0$, we find that $t^* < \Delta$ must hold for (3.10) to hold. □

This result can be explained as follows. In setting the tax, the regulator should not only take into account the harmful effect of emissions, but also the effect of the tax on the firms' ability to invest. Higher taxes reduce firms' profits and tighten firms' credit constraints. To encourage investment, it is optimal to reduce taxes below the marginal environmental cost. More specifically, (3.10) shows that in the optimum, the marginal environmental benefit of increasing the tax, which equals the marginal change in emissions (e_t/z) multiplied by the un-internalized part of the social damages (the marginal damages net of the tax, $\Delta - t$), must equal the cost from discouraging additional investment. This cost equals the marginal value of investment in ($\Pi_Z - C_Z$) multiplied by the change in investment by constrained firms, Z_t^R. If no firms are constrained ($n = 0$), the optimal tax equals marginal emission damages, Δ. Note that the result $t^* < \Delta$ depends on the distribution of firms over z only to the extent that it requires a left tail that in which firms are credit constrained. Other properties of the distribution do not affect this result, but do affect the exact value of t^* that solves for (3.10).

3.5 Economic shocks and environmental policy

As a next step in the analysis we determine the response of the optimal environmental tax to economic shocks. We consider two types of shocks: a credit shock and a productivity shock. The credit shock is a shock to ξ, which is the leverage parameter that determines the amount of credit firms can obtain. The productivity shock is a shock to the productivity parameter a. This shock may be persistent by degree $\mu \in [0, 1)$, such that $dA = \mu da$. In this section, we first take a closer look at the effects of the economic shocks on energy use, profits and investment for given taxes. Next, we turn to the analysis of the optimal response of the first- and second-period emission tax to the credit and productivity shocks.

Market responses to shocks

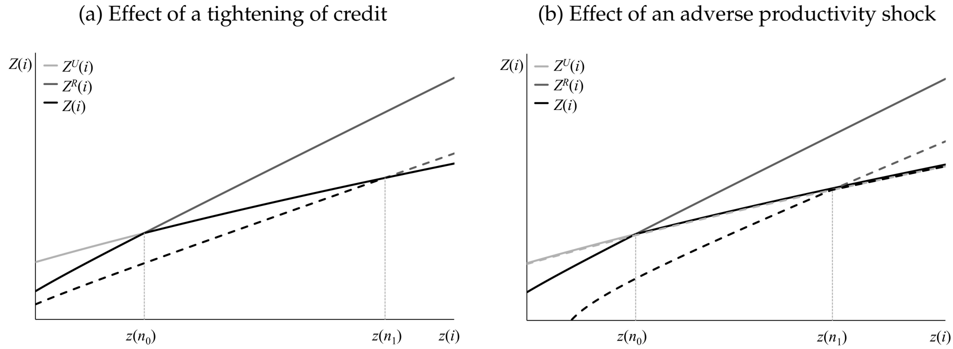
We begin by evaluating the effect of a tightening of credit, i.e. a drop in leverage parameter ξ.[17] A firm's optimal choice of energy is independent of this parameter. Hence, the credit shock leaves first-period energy use and profits unaffected. Investment, however, is affected. If the leverage parameter is lower, less credit is available to firms, and the maximally attainable efficiency level, Z^R, is lower for all firms. More firms are constrained and investment by constrained firms falls. Through this investment effect, the credit shock does affect energy use and profits in the second period: they both fall. The effect of a credit shock on investment is illustrated in Figure 3.2a. It shows that a tightening of credit reduces Z^R for all firms, increases the share of constrained firms from n_0 to n_1, and causes Z to fall for all firms $i \in [0, n_1)$.

The effects are different for a productivity shock, which does alter firms' first-period energy use and profits. An adverse shock to productivity, i.e. a drop in a, reduces the return to energy use and firms choose lower energy input levels. Also output and profits are negatively affected by the adverse productivity shock. The reductions in output and profits may be persistent for two reasons. First, productivity shocks are persistent as long as $\mu > 0$, so lower productivity in the first period implies lower productivity also in the second period, inducing lower second-period energy use and profits. Anticipating the reduction in energy use, unconstrained firms reduce their investments in efficiency improvements, so that Z^U falls. Unconstrained firms will then select a lower investment, which has an additional negative effect on energy use and profits. Second, lower first-period profits imply that firms can obtain less credit. This tightening of the credit constraint reduces Z^R for all firms and forces constrained firms to invest less, which in turn causes their second-period

[17] For expositional purposes, the discussion below will assume that, initially, a subset of firms are constrained ($n \in (0, 1)$).

energy use and profits to fall. Hence, due to credit constraints, even with $\mu = 0$, the effects of adverse productivity shocks may persist.[18] As a persistent negative productivity shock reduces both Z^R and Z^U, the effect of the shock on n, the share of constrained firms, is not clear ex ante. For the example illustrated in Figure 3.2b below, we find that the drop in Z^U is small relative to the drop in Z^R, and thereby n will rise.

Figure 3.2: $Z(i)$ as a function of $z(i)$



Solid lines represent the pre-shock relationship, dashed lines post-shock relationship.

Policy response to credit shocks

Our main interest is in the optimal response of the first-period tax to the economic shocks. Notice that the optimal second-period emission tax, as explained above, equals marginal damages, $T^* = \Delta$. Since marginal emission damage is exogenous, the second-period tax is independent of other parameters and therefore unresponsive to the credit and productivity shocks.

The first-period optimal tax must respond to the shocks. Equation (3.10) characterizes this tax. It equates, at the margin, the cost and benefits of the tax, as explained in detail above. How the optimal tax should respond to the shocks then depends on how the shocks affect these cost and benefits. To solve for the response of t^* to a credit shock we take the total derivative of (3.10) and find

$$t^*_\xi = B^{-1} \left[\int_0^n \left[[\Pi_Z - C_Z] \, Z^R_{t\xi} + [\Pi_{ZZ} - C_{ZZ}] \, Z^R_\xi Z^R_t \right] di \right. \\ \left. + \left[\Pi_Z(Z^R(z(n), \cdot)) - C_Z(Z^R(z(n), \cdot)) \right] Z^R_t n_\xi \right],$$

[18]In the macro literature, this effect is known as the "financial accelerator" (Bernanke et al., 1999).

where $B > 0$.[19]. Again, by Definition 3.2 and Corollary 3.1, we know that either (i) n is the firm that is indifferent between maximal and optimal investment, in which case we have $Z^R(z(n),\cdot) = Z^U(z(n),\cdot)$, which in turn implies $\Pi_Z(Z^R(z(n),\cdot)) - C_Z(Z^R(z(n),\cdot))$, or (ii) $n = \{0,1\}$ and $n_\xi = 0$. Hence, we can reduce t^*_ξ to

$$t^*_\xi = B^{-1} \int_0^n \Bigg[\underbrace{[\Pi_Z - C_Z]\, Z^R_{t\xi}}_{\substack{\text{investment sensitivity} \\ \text{effect } (+/-)}} + \underbrace{[\Pi_{ZZ} - C_{ZZ}]\, Z^R_\xi Z^R_t}_{\substack{\text{investment value} \\ \text{effect } (+)}} \Bigg] di, \tag{3.11}$$

The credit shock only affects the marginal cost of the tax as represented by the term $[\Pi_Z - C_Z]\, Z^R_t$ in (3.10), which is the cost that occurs because the tax crowds out valuable investment of constrained firms. The right-hand side of (3.11) shows that a credit shock may intensify this crowing out through two channels, which possibly work in opposite directions. The second term is positive which tends to make the tax pro-cyclical: the tax increases in response to an increase in the leverage parameter ($t_\xi > 0$). The first term may be negative and then tends to make the tax countercyclical.

The unambiguously positive, i.e. pro-cyclical, channel is named the investment value effect and operates as follows. A positive credit shock increases investment in constrained firms. This decreases the value of investment at the margin, $\Pi_Z - C_Z$, and reduces the value of reduction in the pollution tax as a means to address the underinvestment problem. Hence, the tax becomes pro-cyclical.

The other channel is named the investment sensitivity effect. It reflects the notion that the credit shock might make investment more sensitive to changes in the tax rate. Formally, it is governed by $Z^R_{t\xi}$, which denotes the effect of a credit shock on Z^R_t, which in turn is the sensitivity of maximal investment to the tax. From (3.4) we find

$$Z^R_{t\xi} = \frac{d}{d\xi}\left(\frac{-m\xi}{C_Z}\right) = \frac{Z^R_t}{\xi}\left[1 - \frac{\left(\frac{C_{ZZ}Z}{C_Z}\right)}{\left(\frac{C_Z Z}{C}\right)}\right]. \tag{3.12}$$

The properties of the investment cost function determine the sign of this investment sensitivity effect: if *total* costs (C) do not rise faster with Z than *marginal* costs, the term in brackets is negative and a negative credit shock calls for lower tax through the investment sensitivity effect. This can be explained as follows. On the one hand, harsher credit market conditions make tax easing a less effective in-

[19]More precisely, $B \equiv -\left[\int_0^1 z^{-1}\left[e_t + (t^* - \Delta)\, e_{tt}\right] di + \int_0^n \left[[\Pi_{ZZ} - C_{ZZ}]\, Z^R_t Z^R_t + [\Pi_Z - C_Z]\, Z^R_{tt}\right] di\right]$. As t^* maximizes $v \equiv \int_0^1 [\pi + s + \Pi - C + S - \Delta\,(m + M)]\, di$ subject to (3.4) we must have that at $t = t^*$, $v_t = 0$ and $v_{tt} < 0$. Here one can show $B = -v_{tt}$.

strument to stimulate investment. On the other hand, as there is less investment in the first place (the shock reduces Z), the marginal cost of additional investment is low too, and a decline in the tax rate now causes a larger change in investment. If marginal investment costs increase sufficiently fast with investment, the latter effect dominates and taxes should be lower under harsher credit market conditions.

Taking together the two effects, we can write:

$$t^*_\xi = B^{-1} \int_0^N \frac{-Z_t^R}{\xi} \left[\frac{\Pi_Z}{C_Z Z/C} \left(\frac{C_{ZZ}Z}{C_Z} + 1 - \frac{C_Z Z}{C} \right) + C_Z + \frac{-M_Z T}{C_Z Z/C} \right] \tag{3.13}$$

which shows that the sign of the total effect is ambiguous in principle. Note that the term in parentheses is the elasticity of the elasticity (or "superelasticity") of the marginal investment cost with respect to Z. If the cost function is iso-elastic, the superelasticity is zero. Together with our assumption $M_Z < 0$ this makes the optimal tax pro-cyclical. This result holds, by continuity, for an almost iso-elastic cost function and, a fortiori, for a positive superelasticity, i.e. when investment costs are strongly convex.[20] This directly proves the following proposition:

Proposition 3.2. *Under Assumption 3.1, a sufficient condition for $t_\xi > 0$ is a positive super-elasticity of the marginal investment cost, $d\ln(C_Z Z/C)/d\ln Z \geq 0$.*

Proof. In text. □

Intuitively, convex investment costs make investment expensive in booms so that it becomes costlier to address the underinvestment problem through a low tax. However, (3.13) also reveals under which conditions the optimal tax responds countercyclically to credit shocks. This is the case if the super-elasticity is sufficiently negative for credit-constrained firms.[21]

Policy response to productivity shocks

Following the same procedure, we determine the response of the optimal tax to a productivity shock. In addition to the investment sensitivity effect and the investment value effect, we can identify an emission sensitivity and a persistence effect:[22]

[20] A positive superelasticity means that marginal cost C_Z rises faster with Z than average cost C/Z.

[21] Moreover, $M_Z < 0$ follows from Assumption 3.1. If we were to relax this assumption, and if in the left tail of the distribution a significant share of firms would have $M_Z > 0$, the tax might become countercyclical.

[22] Note we again use the result that either $\Pi_Z = C_Z$ for firm $i = n$, or $n_a = 0$.

$$t_a^* = B^{-1}\left[\begin{array}{c}\underbrace{(t^*-\Delta)\int_0^1 \frac{e_{ta}}{z}di}_{\substack{\text{emission sensitivity}\\ \text{effect } (+/-)}} \\ +\int_0^n\left[\underbrace{[\Pi_Z - C_Z]\,Z_{ta}^R}_{\substack{\text{investment sensitivity}\\ \text{effect } (+/-)}} + \underbrace{[\Pi_{ZZ}-C_{ZZ}]\,Z_a^R Z_t^R}_{\substack{\text{investment value}\\ \text{effect } (+)}} + \underbrace{\mu \Pi_{ZA} Z_t^R}_{\substack{\text{persistence}\\ \text{effect } (-)}}\right]di\end{array}\right]. \quad (3.14)$$

The investment sensitivity and investment value effects for the productivity shock are very similar to those for the credit shock. As before, the investment value effect captures that a positive shock raises investment, lowers the marginal value of investment, makes investment stimulation less important and increases the optimal environmental tax - the tax responds pro-cyclically to the productivity shock.

The investment sensitivity effect is again ambiguous in sign. It evaluates the effect of the shock on Z_t^R and includes two counteracting effects:

$$Z_{ta}^R = \frac{d}{da}\left(\frac{-m\xi}{C_Z}\right) = \frac{Z_t^R}{a}\left[\frac{y_e}{-y_{ee}e} - \frac{\left(\frac{C_{ZZ}Z}{C_Z}\right)}{\left(\frac{C_Z Z}{C}\right)}\frac{y}{\pi}\right]. \quad (3.15)$$

The two terms in brackets represent two opposite forces. As a direct effect, a drop in a implies lower energy use. With lower energy use, the loss in profits due to a marginal tax increase is reduced. As the profit level directly determines investment, the drop in productivity reduces the sensitivity of investment to the tax. This is however not the full story. A lower productivity also implies that profits, and thus investment, are lower to begin with. Because of convexity of the investment costs, this translates into a lower marginal cost of investment, which makes a given increase in profits affect investment more.

The emission sensitivity effect and the persistence effect in (3.14) are unique to the productivity shock. The latter effect captures the persistence of productivity shocks: a negative productivity shock reduces second-period productivity, reducing the marginal return to investment. This reduces the merit of the tax in addressing the underinvestment problem and the tax moves counter-cyclically.

Finally, the emission sensitivity effect captures the effect of the productivity shock on the benefits of levying the tax in the first place, i.e. the marginal benefits of the tax in reducing firm emissions $(t^* - \Delta)e_t/z$. If $e_{ta} < 0$, a positive productivity shock makes emissions more sensitive to the tax, so that the tax is more effective in addressing the environmental externality. In this case the tax responds pro-cyclically to productivity shocks. However, the sign of e_{ta} depends on the properties of the production function as becomes clear from

$$e_{ta} = \frac{d}{da}\left(\frac{1}{zy_{ee}}\right) = \frac{e_t}{a}\left[\frac{\left(\frac{y_{eee}e}{y_{ee}}\right)}{\left(\frac{y_{ee}e}{y_e}\right)} - 1\right] = \frac{e_t}{a}\epsilon\left[\frac{d\ln\epsilon}{d\ln e} + 1\right]. \tag{3.16}$$

where ϵ is the positively defined price elasticity of energy demand, $\epsilon \equiv -y_e/ey_{ee}$, which is a function of e only. The elasticity of this elasticity equals $d\ln\epsilon/d\ln e = y_{ee}e/y_e - y_{eee}e/y_{ee} - 1$. As long as the price elasticity ϵ does not fall too quickly with emissions, we have $e_{ta} < 0$, the case just discussed. However, in the case in which a one percent increase in energy use decreases the price elasticity of energy use by more than 1 percent, the tax sensitivity decreases when the economy becomes more productive, which tends to make the tax counter-cyclical.

Comparing (3.11) to (3.14), one can see that the emission sensitivity and persistence effects are absent with the credit shock. As credit shocks do not affect firms' decisions regarding e, it also leaves e_t unaffected and therefore no emission sensitivity effect is present. The persistence effect follows from the increase in the marginal benefit from investment due to the increase in (expected) second-period productivity. Credit shocks do not affect firm's (future) productivity, and thus do not affect the marginal value of investment through this channel.

All in all, additional assumptions are required regarding the forms of the production and investment cost functions to determine the sign of t^*_ς and t^*_a. Section 3.6 solves for t^*_ς and t^*_a for a specific functional form. For this functional form, the positive effects dominate: taxes should fall in response to adverse credit or productivity shock.

Proposition 3.3. *If $y(a, e(i)) = h(a)f(e(i))$ is iso-elastic with respect to $e(i)$ and if some firms are constrained, the sum of investment sensitivity and emission sensitivity effect is positive and for sufficiently low persistence the optimal first-period tax falls in response to an adverse productivity shock.*

Proof. Iso-elasticity of $f(e(i))$ implies constant elasticity ϵ, so that (3.16) boils down to $e_{ta} = e_t\epsilon/a$ and the emission sensitivity effect reads $B^{-1}(t^* - \Delta)(\epsilon/a)\int_0^1 z^{-1}e_t di$. Substituting (3.10), we can show this is equal to $-B^{-1}(\epsilon/a)\int_0^n [\Pi_Z - C_Z]\, Z_t^R di > 0$. Adding to this the investment sensitivity effect, using (3.15) and $d\ln\epsilon/d\ln e = y_{ee}e/y_e - y_{eee}e/y_{ee} - 1 = 0$, we find for this sum: $-B^{-1}\int_0^n [\Pi_Z - C_Z] \frac{\left(\frac{C_{ZZ}Z}{C_Z}\right)}{\left(\frac{C_Z Z}{C}\right)} \frac{y}{\pi} Z_t^R di > 0$. The positive investment value effect and the negative persistence effect have to be added to find the total effect as defined in

(3.14). It follows immediately that if the persistence effects is small, the RHS of (3.14) is positive, which implies $t_a^* > 0$. □

3.6 An example

We conclude the evaluation of the model with a short example. In this example, we define specific functional forms for the production and investment cost function, and determine whether, for this specification, the optimal first-period tax rises or falls following an adverse credit of productivity shock.

Production reads[23]

$$y(a, e(i)) = [\exp(a)]^{1-\beta} e(i)^{\beta}, \tag{3.17}$$

where $\beta \in (0, 1)$. Investment cost are defined as

$$C\left(z(i), Z(i)\right) = \left(Z(i)/z(i)\right)^{\gamma}. \tag{3.18}$$

The optimizing firm sets $y_e = q + t/z$, which gives equilibrium energy use:

$$e(z(i), t, a) = \exp(a)\left[\frac{\beta}{q + t/z(i)}\right]^{\frac{1}{1-\beta}}. \tag{3.19}$$

Profits can then be reduced to

$$\pi(z(i), t, a) = (1-\beta)\exp(a)\left[\frac{q + t/z(i)}{\beta}\right]^{-\frac{\beta}{1-\beta}} - \phi. \tag{3.20}$$

Naturally, all the relationships between energy use and profits on the one side, and tax rates and emission efficiency on the other side, as established in Section 3.5 for the general case, carry over to the specific case discussed here. In addition, we can show Lemma 3.2 applies: the lowest $z(i)$ firms are most likely constrained. Figures 3.1 and 3.2 show the relationship between z and Z, Z^R and Z^U for the functional forms defined above.

To pin down the sign of t_{ξ}^* , we first determine the sign of the investment sensitivity effect for the credit shock. From the credit constraint (3.4), we know $Z_t^R = \xi \pi_t C_Z^{-1} < 0$. Then, with the use of (3.18), we find that $Z_{t\xi}^R = [\xi\gamma]^{-1} Z_t^R < 0$: the investment sensitivity effect is negative. Following an adverse (favorable) shock to credit, investment is less (more) sensitive to the tax, which argues in favor of higher

[23]For the sake of brevity, the equations are expressed in terms of first-period variables. All equations equally apply for the second-period variables. For example, the second-period equivalent of (3.17) is $Y\left(A, E\left(i\right)\right) = \exp\left(A\right)^{1-\beta} E(i)^{\beta}$.

(lower) taxes. This negative investment sensitivity effect does however not outweigh the positive investment value effect, as we arrive at the following result:

Proposition 3.4. *Under specifications (3.17)-(3.18), as long as some firms are constrained, the optimal first-period tax falls in response to an adverse credit shock.*

Proof. By $Z^R_{t\xi} = [\xi\gamma]^{-1} Z^R_t$, the investment sensitivity effect reads $B^{-1}\int_0^n [\Pi_Z - C_Z]\,[\xi\gamma]^{-1} Z^R_t di$. Next, by (3.4) and (3.18), we have $C_Z + ZC_{ZZ} = \gamma C_Z$ and $Z^R_\xi = [\xi\gamma]^{-1} Z^R$. In addition we know $Z\Pi_{ZZ} = TM_Z - \Pi_Z$. We use these results to reduce the investment value effect to $B^{-1}\int_0^n [TM_Z - \Pi_Z - (\gamma - 1)\,C_Z]\,[\xi\gamma]^{-1} Z^R_t di$. Adding both effects then gives us $t^*_\xi = [B\xi\gamma]^{-1}\int_0^n [TM_Z - \gamma C_Z]\, Z^R_t di$. As $M_Z < 0$, $C_Z > 0$ and $Z^R_t < 0$, the integral is positive and $t^*_\xi > 0$.[24] □

One the one hand, a drop in ξ, by reducing the effect of a given increase in profits on credit available to firms, reduces the sensitivity of Z^R to the tax. Hence, during financial crises, tax reductions are less effective in alleviating credit constraints. However, because a fall in ξ reduces investment to begin with, the marginal value of additional investment rises. By Proposition 3.3, the latter effect dominates, and the optimal emission tax falls in response to a financial contraction. Note that as first-period emissions are independent of ξ, but falling in t, we can directly conclude that an optimal first-period emission *quota* rises following an adverse shock to credit.

For the productivity shock, we identified four effects, of which two were ambiguous. As for the credit shock, we can establish that the investment sensitivity effect is negative for the specific functional form: using (3.4), (3.17) and (3.18), we find $Z^R_{ta} = Z^R_t/\gamma < 0$. This implies that following an adverse productivity shock, larger tax reductions are necessary to achieve a given increase in Z^R; Z^R has become less sensitive to the tax and a higher tax is optimal. Also the emission sensitivity effect was ambiguous. From (3.19) we can show that $e_{ta} = e_t < 0$, which by $t^* < \Delta$ gives a positive emission sensitivity effect. So following an adverse productivity shock, also emissions are less responsive to changes in the tax; the tax becomes a less effective tool for reducing emission, and a lower tax is optimal. Put together, we identified two positive (emission sensitivity and investment value) and two negative (investment sensitivity and persistence) effects. As formulated by the following proposition, the positive effects outweigh the negative effects: $t^*_a > 0$.

Proposition 3.5. *Under specifications (3.17)-(3.18), as long as some firms are constrained, the optimal first-period tax falls in response to an adverse productivity shock.*

[24] Alternatively, by (3.18), we have $ZC_Z/C = \gamma$. It then directly follows from Proposition 3.2 that $t_\xi > 0$.

Proof. By $e_{ta} = e_t$, the emission sensitivity effect reads $B^{-1}(t^* - \Delta)\int_0^1 z^{-1} e_t di$. Substituting (3.10), we can show this is equal to $-B^{-1}\int_0^n [\Pi_Z - C_Z] Z_t^R di > 0$. Next, we have $Z_{ta}^R = Z_t^R/\gamma$, so the investment sensitivity effect equals $B^{-1}\int_0^n [\Pi_Z - C_Z]\gamma^{-1} Z_t^R di < 0$. As $\gamma > 1$, this implies the positive emission sensitivity effect is stronger than the negative investment sensitivity effect. For the investment value effect we use $C_Z + ZC_{ZZ} = \gamma C_Z$, $Z\Pi_{ZZ} = TM_Z - \Pi_Z$ and $Z_a^R = Z/\gamma$. This gives $B^{-1}\int_0^n [TM_Z - \Pi_Z - (\gamma-1) C_Z]\gamma^{-1} Z_t^R di > 0$ as the investment value effect. The persistence effect then equals $B^{-1}\int_0^n \mu \Pi_Z Z_t^R di < 0$, where we used $\Pi_{ZA} = \Pi_Z$. Jointly, these two effects equal $B^{-1}\int_0^n [TM_Z - (1-\gamma\mu)\Pi_Z - (\gamma-1) C_Z]\gamma^{-1} Z_t^R di > 0$. Here, $\gamma\mu \leq 1$ would be a sufficient condition for the positive investment value effect to outweigh the negative persistence effect. Adding all effects, we arrive at $t_a^* = B^{-1}\int_0^n \left[\Pi_Z(\mu-1) + \gamma^{-1} TM_Z\right] Z_t^R di$, which by $\mu \leq 1$ is always positive. □

As $y(a, e(i))$ in (3.17) is iso-elastic with respect to e, from Proposition 3.3, we can immediately conclude that the positive emission sensitivity effect always outweighs the negative investment sensitivity effect. Then, the lower persistence μ, and the smaller the curvature of the cost function γ, the more likely that the positive investment value effect outweighs the negative persistent effect. In any case, jointly, we always have $t_a^* > 0$; it is optimal to reduce (increase) the tax following and adverse (favorable) productivity shock. Contrary to the credit shock, we cannot directly determine the effect of the productivity shock on the first-period optimal emission *quota*. As the adverse productivity shock directly reduces first-period emissions, but the reduction in the tax in turn increases emissions, the aggregate effect is ambiguous.

3.7 Discussion

To explore the implications of productivity and credit shocks for optimal environmental policy when firms face constraints to credit, we adopted a partial equilibrium approach in a stylized two-period model of investment. In this section, we discuss some of our assumptions and we consider extensions to a more general setting.

Marginal damage cyclicality

In our framework, we assume throughout that marginal damages from emissions are unaffected by the credit or productivity shocks. Put differently, we assume marginal damages are a-cylical. An alternative assumption is that marginal damages are pro-cyclical.[25] Below, we will briefly discuss the potential drivers of the cyclicality of marginal damages and explain how pro-cyclical damages may alter our results.

To determine the likely cyclicality of emission cost, it is material to know whether the relevant externality can be considered a flow or stock externality. Flow externalities, such as water pollution, are short-lived; the period in which the pollutant is emitted roughly coincides with the period during which damages are incurred and the pollutant again depreciates. It is conventionally assumed that for these flow pollutants, marginal damages increase in emissions and output. As emissions and output rise during booms and fall during recessions, one should thus expect these damages to be pro-cyclical.

The story is distinct if one considers stock externalities, such as climate change caused by the emission of CO_2, which is the motivating example in this chapter. The impact of CO_2 emissions today are both delayed and persistent; global temperature levels respond slowly to increases in atmospheric CO_2 concentrations, and atmospheric CO_2 in turn depreciates slowly. This implies that the relevant output level to determine damages from CO_2 emitted today is not today's output, but expected output in one to several decades from today. Hence, unless temporary shocks have substantial long-run effects, these shocks should not affect marginal damages through output. Also fluctuations in CO_2 emissions need not affect marginal damages from these emissions; some recent research has pointed out that the convex relationship between temperature and damages, and concave relationship between CO_2 concentrations and temperatures jointly imply that damages are approximately linear in emissions, and marginal damages thus independent of the emission stock (Gerlagh and Liski (2012); Golosov et al. (2014); Van den Bijgaart et al., 2016).[26]

Depending on the exact model, marginal emission cost may be expressed in utils, or units of present-time consumption. In the latter case, the current marginal utility of consumption plays a role: if the marginal utility of consumption is high, emission costs in consumption units are low. With concave utility we then see a form of consumption smoothing; emission costs are lower in recessions than in booms. Our partial equilibrium model however, abstracts from consumption smoothing by fo-

[25]The existing literature on business cycles and environmental policy mostly abstracts from the question of damage cyclicality by focusing on the cost effectiveness of policies reducing emissions to a certain level (e.g. Angelopoulos et al. (2010); Dissou and Karnizova (2012); Fischer and Springborn (2011)). An exception is Heutel (2012), who models the emission of CO_2, which cause damages that are quadratic in the current emission stock. This damage specification, as we explain below, may lead to an overstatement of the (pro-)cyclicality marginal damages.

[26]Even if one would assume marginal emission damages increase in cumulative emissions, the effect of a positive productivity shock on marginal damages is not immediate. Due to credit constraints, the positive productivity shock does not only increase emissions, but also investment in emission efficiency. Because of these efficiency improvements, and corresponding emission reductions, the effect of a productivity shock on cumulative emissions is ambiguous

cusing on production maximization instead of utility maximization. This approach is equivalent to assuming a utility function that is linear in consumption. Alternatively, one could reinterpret our model as a representation of one of many markets, where the shock is idiosyncratic to the market. In this case, aggregate consumption, and hence the marginal utility of consumption, would be virtually unaffected by the shock. Explicitly defining a utility function with diminishing marginal utility would be an interesting extension to the model, and open up a rationale for using investment and emission taxes as a means for smoothing consumption over time.

(Pro-)cyclical damages can be included in our framework, but its effect on response of the optimal tax to the economic shocks is ambiguous. For the second-period tax, $\Delta_a > 0$ would directly translate into $T_a^* > 0$. For the first-period tax however, two counteracting forces would be introduced. On the one hand, $\Delta_a > 0$ would call for an increase in the tax following a positive productivity shock. On the other hand, an increase in the second-period tax increases the marginal benefit from investment, and thereby benefits of alleviating credit constraints through reductions in the first-period tax.

Opportunity cost of investment

According to the Schumpeterian view (see Aghion and Howitt, 1998), investment costs are procyclical, as opportunity costs, of for example labor, rises during booms. In our analysis, we abstracted from this issue, and, (implicitly) assumed that investment costs are independent of ξ, a, or A. The main motivation behind this is that there is ample empirical evidence that investment in productivity improvements takes place during booms (see for example Aghion et al., 2012). This indicates that that channels, such as credit constraints, that favor investment in booms are stronger than those that turn investment countercyclical, such as procyclical investment costs. Still, assuming that $C_{Za} > 0$ instead of $C_{Za} = 0$ would not alter any of our conclusions as it adds two additional effects towards $t_a^* > 0$. First, an increase in marginal investment costs following a favorable productivity shock, reduces the marginal benefit net of costs from investment, and thereby the benefit of alleviating credit constraints, vis-a-vis the case where $C_{Za} = 0$. Second, with $C_{Za} > 0$, Z_{ta}^R is increased.[27] By (3.14), this implies the investment sensitivity effect is more likely positive.

[27] In more detail, we have $Z_{ta}^R = -C_Z^{-1}\left[\xi e_a z^{-1} + \left[C_{ZZ} Z_a^R + C_{Za}\right] Z_t^R\right]$. As $Z_t^R < 0$ and $C_Z > 0$, Z_{ta}^R is increasing in C_{Za}.

Tax revenue recycling

As explained in Section 3.2, we assume the emission tax revenues are recycled lump sum, yet firms cannot in turn use these recycled funds for investment nor collateral. In Appendix 3.A we abandon this assumption, and allow the lump-sum to be used for investment and collateral. This implies that an increase in taxes may alleviate credit constraints for some firms: higher taxes now don't only imply lower profits, but also higher rebates, which alleviate credit constraints. Still, we find that, qualitatively, all results continue to apply.

This robustness is intuitive: firms with low initial efficiency do, due to the constraints, not only choose investment further from the unconstrained optimum, but also have higher emissions, and therefore pay higher taxes. As a consequence, emission taxes reallocate funds from relatively constrained firms, to relatively unconstrained firms, and an increase in the tax further reinforces this reallocation. So even though some firms benefit from such a recycling scheme and potentially invest more, firms where further investment has the greatest social value will be forced to choose a lower Z. Hence, in the aggregate, a reduction in t still brings about societal benefits as it reduces the credit constraints of the most constrained firms.

This intuition then extends to the analysis of how the tax is optimally adjusted to the shocks. For the specific functional form also adopted in Section 3.6, again the effects on the most constrained firms dominate. As the firms in the 'standard' model, these are the firms who face tighter constraints due to tax increases, and hence results are similar.

Multi-period general equilibrium approach

While we have derived our results in a two-period setting, the main mechanisms operate in a similar way in a more general multi-period setting. Crucial in our reasoning is that some firms are constrained in their investment decision and that the credit and productivity shocks affect equilibrium investment and emissions for these firm - this will apply equally in a multi-period setting. In particular, each firm's initial level of efficiency is the starting point for its multi-period investment plan, and the distribution of efficiency levels will shift over time. In line with the conventional macroeconomic investment model, firms smooth investment due to adjustment costs, so that investment is in principle constrained for multiple periods. Over time firms may grow out of these constraints, with high-z firms becoming unconstrained earlier than low-z firms. The trade-off between control of emissions and investment through the tax extends to multiple periods and the optimal tax can be expected to be below the Pigouvian level for multiple periods until no firm is constrained any more.

We also derived our results in a partial equilibrium result and abstracted from general equilibrium interactions. Reallocations of production factors other than emissions (e.g. labor or capital) and relative price changes in response to shocks and tax rate changes are not made explicit but are subsumed in our $f(.)$ function. A full-fledged macro-economic analysis is beyond the scope of this chapter, but we suggest that future work in this direction could build on the recent work by Itskhoki and Moll (2014). They study optimal policies in a growth model with financial frictions. They show that to alleviate credit and investment constraints, such policies should increase labor supply and lower wages. Their framework can be extended to include energy, or emissions, as an input to production and to include productivity and credit shocks.

Asymmetric productivity shocks

The shocks considered in the framework are symmetric across firms. Hence, the only source of heterogeneity across firms is the first period emission efficiency $z(i)$. Expressions (3.11) and (3.14) still apply if only a subset of the firms is subject to the shock. In these cases, in (3.11), Z_ξ and $Z_{t\xi}$ will only be nonzero for a subset of firms and a similar reasoning applies to Z_a, Z_{ta}, Π_{ZA} and e_{ta} in (3.14). Propositions 3.4 and 3.5 then continue to hold, yet only with a small addition: "As long as some firms, *which are subject to the shock*, are constrained [...]".

The exercise above still presumes the shock is symmetric across the firms who are subject to it. If shocks are asymmetric, n need no longer well-defined, and neither would t_ξ and t_a be easily signed. For the individual firms however, the separate emission sensitivity, investment sensitivity, investment value and persistence effects can still be identified. Also their underlying intuition extends to the case of asymmetric shocks.

3.8 Conclusion

This chapter evaluates optimal environmental policy in a two-period setting with heterogeneous firms. Firms use energy in production, with harmful emissions as a byproduct. To reduce these emissions, firms can invest in pollution-saving technologies, but investment may be suboptimal due to credit constraints. In this setup, a higher first-period emission tax has two effects: it reduces energy use and emissions, but, by reducing profits, reduces investment of firms subject to binding credit constraints. The framework thus features a trade-off between relieving firms' credit constraints and reducing harmful emissions. We find that if constraints are binding for a subset of firms, the optimal first-period emission tax falls short of marginal damages. The response of the optimal emission tax to a credit or productivity shock then depends on several factors. More specifically, we identify four potential channels through which a shock to productivity or credit may affect the optimal emission tax. The first, the investment value effect, captures the fact that a positive shock to productivity or credit relaxes the firms' credit constraints and thus increases the optimal tax following such a shock. The second effect is the investment sensitivity effect. It captures whether, following a shock to productivity, the constrained firms' choice of second-period emission efficiency is more or less sensitive to the first-period tax. This effect is positive as long as investment cost rise sufficiently fast with investment. Then, following a positive productivity or credit shock, investment responds more strongly to the tax, which then implies a lower tax is optimal. Third, we have the emission sensitivity effect. In line with the investment sensitivity effect it determines whether emissions are more or less responsive to the tax following a shock. This effect is absent for credit shocks; for productivity shocks it is ambiguous for a general specification, and calls for higher taxes following a positive productivity shock for the specific functional form. The fourth and final effect is the persistence effect: if a positive productivity shock is persistent, the return to investment is increased, and a lower first-period tax, which increases investment by constrained firms, is optimal. All in all, for the specific functional form, the positive effects dominate, and taxes should rise in response to a positive credit or productivity shock.

In the policy debate regarding the desirability of environmental policy in an economic downturn, a major argument raised is that as (more stringent) environmental policies impose further hardship on business, they should be either postponed or canceled. Our result lends support to this argument by showing that the optimal emission tax should fall following an adverse shock to productivity or credit. This however, need not imply that further environmental legislation should be postponed until more virtuous times have arrived. Our analysis evaluates the optimal tax, and there is no reason to suppose emissions are currently optimally priced. To determine the desirability of strengthening, or weakening, environmental regulations, an assessment regarding the stringency of this regulation, relative to its optimal level, is required. In such an evaluation, as our analysis points out, the regulation's effect on firm's access to credit may be an important factor, and should thus be included in such assessment.

Our result that the optimal tax rises in response to a positive shock is consistent with Heutel (2012), yet the underlying mechanism is distinct. Heutel (2012) found a that taxes should rise (fall) in response to a favorable (adverse) productivity shock.

This result however is fully driven by the pro-cyclicality of the marginal emission cost. In our framework, the marginal emission cost is independent of the shocks. Instead, our results are due to the presence of the credit constraint; in setting the tax, the regulator faces a trade-off between reducing emissions and alleviating the credit constraint, and this trade-off may be affected by the shocks.

Our partial equilibrium framework is stylized and abstracts from many elements that may be relevant in a full-fledged analysis of environmental taxes along the business cycle. Several of such elements, such as the damage cyclicality, tax revenue recycling, multi-period investment decisions, and general some equilibrium effects have been discussed in Section 3.7. We explored tax revenue recycling in Appendix 3.A and found our qualitative results to be robust to this case. Several features are worth a formal analysis in future work. In addition to those extensions already discussed in Section 3.7, we would like to point out that we focused our analysis on the optimal tax policy. An assessment of the response of the optimal emission quota would be a natural extension. Here, as absent of tax adjustments, emissions rise in following a positive productivity shock, a pro-cyclical emission tax need not directly translate in to a counter-cyclical optimal emission quota.

Appendix 3

3.A Environmental policy with lump-sum recycling

In the main part of the chapter, we assume the tax recycling scheme leaves the credit constraint, (3.4), unaffected. This assumption is justified if the tax revenues are a direct benefit to the government, or the rebate only occurs once the investment is made (and/or the loan is repaid). Alternatively, if only a small subset of firms are subject to the tax, whereas the returns are spread across a large group of firms, the rebate is of negligible size and can hence be ignored in (3.4). In any case, this setup greatly simplifies the analysis as it allows us to abstract from the redistributional effect of the tax; as a firm's tax payment is a function of its emission efficiency, z, not all firms are taxed equally, and the lump sum rebate constitutes a redistribution of funds across firms. In this appendix, we re-establish Propositions 3.1, 3.4 and 3.5 for the case in which the lump sum *can* be used to invest and obtain credit. More specifically, the constraint defined by (3.4) will be replaced by

$$C\left(z(i), Z(i)\right) \leq \xi\left[\pi(i) + s\right], \tag{3.A.1}$$

where the lump sum rebate

$$s = t\int_0^1 e(i)z(i)^{-1}di \tag{3.A.2}$$

is considered exogenous by the firm.[28] This appendix is structured similar to the main text. We first solve for the firm optimization problem for given t and T. Next, we determine t^* and T^*, as well as the response of the optimal tax to credit, ξ, and productivity, a, for both the general and specific functional form.

3.A.1 Equilibrium

The firms' optimization problem now reads:

$$\max_{e,E,Z} \pi + s + \Pi - C + S \tag{3.A.3}$$

subject to (3.A.1). Output, profits and investment costs are defined as in (3.1)-(3.3). Firms take the lump sum as exogenous, so the first order conditions in (3.5) still apply: $\pi_e = 0$ and $\Pi_E = 0$. Also $C_Z = \Pi_Z$ still holds for unconstrained firms

[28]Note that as the lump sum can be used for loan collateral, this is a more 'generous' redistribution scheme than a direct investment subsidy that reduces investment cost to $C - s$.

(see (3.6)). For constrained firms we now have $C = \xi [\pi + s]$. From the above, we can directly conclude that the lump-sum rebate alleviates the credit constraint. As all firms receive the same lump sum, Corollary 3.1 still applies: firms $i \in [0, n)$ are credit constrained, and firms $i \in [n, 1]$ are unconstrained. With the tax recycling scheme in place, an additional separation across firms becomes relevant: firms to whom an increase in the first-period tax is a net benefit, versus firms to whom it is a net cost. The most straightforward way to see this is if we consider only 2 (types of) firms: one with zero emissions (i.e. $z = \infty$) and one with positive emissions (i.e. some $z < \infty$). Now the introduction of an emission tax imposes a cost on the latter group only. However, both firms receive the rebate. It must thus follow that the tax introduction is a net gain to firms with $z = \infty$, and a net cost to firms with $z < \infty$. This rationale holds for any first-period tax increase as long as total tax payments, and hence the size of the rebate, is increasing in the tax rate. The following lemma establishes that this is indeed the case:

Lemma 3.A.1. $s_t > 0$

Proof. By (3.A.2) we have $s_t = \int_0^1 z^{-1} [e + te_t] \, di$. By (3.2) and (3.5) we have $e_t = [zy_{ee}]^{-1}$ and $e_z = -z^{-2} y_{ee}^{-1} t$ which implies $te_t = -ze_z$. Next we use $m_z = z^{-2} [ze_z - e]$, so $s_t = -\int_0^1 zm_z di$. Now by Assumption 3.1, $m_z < 0$, so $s_t > 0$. □

The above result can be explained as follows. The effect of an increase of z on emissions is twofold. On the one hand, a greater emission efficiency reduces emissions, given energy use. On the other hand, a higher z reduces the marginal cost of energy use, which increases firms' choice of e. For emissions to fall in z we thus need e to be relatively insensitive to changes in the tax component of energy costs, t/z. In a similar manner, the effect of an increase in t on tax revenue, s, can be separated in two effects. One the one hand, given emissions, an increase in t increases tax revenue. On the other hand, the increase in t reduces energy use, reducing emissions and tax revenues. By assuming $m_z < 0$, we implicitly assume e is relatively insensitive to changes in t/z, and as a consequence we also find $s_t > 0$. Note that this does not mean the downward-sloping part of the Laffer curve does not exist in our specification. Instead, it implies that we restrict our analysis to the case with $m_z < 0$ and thereby $s_t > 0$.

Next we define

Definition 3.A.1. Let $\tilde{z}$ be the first-period efficiency such that for a firm with $z = \tilde{z}$, a marginal change in t leaves maximal investment unaffected, i.e. $Z_t^R(\tilde{z}, t, a, \xi) = 0$.

Lemma 3.A.1 then allows us to prove

Lemma 3.A.2. *$\tilde{z}$ is unique and strictly larger than $\underline{z}$. For firms with $z < \tilde{z}$, we have $Z_t^R < 0$, while for firms with $z > \tilde{z}$, $Z_t^R > 0$.*

Proof. First we use (3.A.1) to establish $Z_t^R(i) = C_Z^{-1}(i)\xi\left[\pi_t(i) + s_t\right]$. Next, by $\pi_t = -m$, we have $\pi_{tz} = -m_z > 0$. With s and thus s_t common across firms, this implies that $[\pi_t(i) + s_t]$ is more likely negative for low z firms. As $\int_0^1 [\pi_t(i) + s_t]\, di = \int_0^1 z^{-1}\left[te_t(i)\right] di < 0$, Z_t^R must be negative for the firm with the lowest z: $i = 0$. For $z = \infty$, emissions are zero, so $Z_t^R = C_Z^{-1}\xi s_t > 0$. So by continuity, there must exist some unique emission efficiency $\hat{z} < \infty$, which satisfies $Z_t^R = 0$. □

Corollary 3.A.1 then follows directly from Lemma 3.A.2:

Corollary 3.A.1. *Let g be the the share of firms whose maximal investment falls in t, such that for firms $i \in [0, g)$, $Z_t^R < 0$, while for firms $i \in (g, 1]$, $Z_t^R > 0$. Then, if $\tilde{z} > \bar{z}$, $g = 1$, otherwise $z(i) = \tilde{z}$ for $i = g$.*

Since emissions are falling in emission efficiency z, the least efficient firms pay the most taxes. As profits are rising in z, this implies that the tax scheme is regressive: it harms high profit (high z) firms less than low profit (low z) firms. With a lump sum recycling scheme, we thus find that more efficient firms are more likely to see $\pi + s$ increase with tax increases. Hence, for these firms, Z^R may be increasing in the first-period tax rate, t.

3.A.2 Optimal environmental policy

The regulator still solves (3.8), yet now subject to (3.A.1). In line with the main text, we use (3.5) and $S = T\int_0^1 Z^{-1}E di$, to reduce the first order condition with respect to T to $(T^* - \Delta)\int_0^1 Z^{-1}E_T di = 0$. Hence, we can conclude that still $T^* = \Delta$. Also for t^*, we again arrive at (3.10). To make the distinction between firms for whom $Z_t^R < 0$ and those who have $Z_t^R > 0$ explicit, we rewrite (3.10) to

$$-(t^* - \Delta)\int_0^1 \frac{e_t}{z} di = \int_{\min\{n,g\}}^{n} \left[\Pi_Z - C_Z\right] Z_t^R di + \int_0^{\min\{n,g\}} \left[\Pi_Z - C_Z\right] Z_t^R di. \quad (3.A.4)$$

Because Z_t^R is positive for firms $i \in (g, n]$ and negative for firms $i \in [0, g)$, the sign of the RHS of (3.A.4) is not directly obvious. Hence we can wonder whether the fact that some constrained firms gain from tax increases may imply that the optimal tax exceeds marginal damages. By some tedious algebra, we can however show that Proposition 3.1 continues to apply:

Proposition 3.A.1. *As long as some firms are constrained, the optimal first-period tax falls short of the Pigouvian tax ($t^* < \Delta$).*

Proof. Two cases can be distinguished. First, if $n \leq g$, Z^R is decreasing in t for all constrained firms. In this case, the proof to Proposition 3.1 applies. If $g < n$, Z^R is increasing in t for some constrained firms and the proof runs as follows.

1. As $g < n$, we must have $\Pi_Z(z(g), \cdot) - C_Z(z(g), \cdot) > 0$. Next, we have $\int_0^1 Z_t^R di = \xi \int_0^1 C_Z^{-1}[\pi_t + s_t] di$. Here we know $\int_0^1 [\pi_t + s_t] di = \int_0^1 te_t di < 0$ and $[\pi_t + s_t]$ is smaller (more negative) the smaller $z(i)$. As $C_{ZZ} > 0$ and $Z_z^R > 0$, C_Z^{-1} is larger the smaller $z(i)$. Hence, we must have $\int_0^1 Z_t^R di < 0$ and $[\Pi_Z(z(g), \cdot) - C_Z(z(g), \cdot)] \int_0^n Z_t^R(i) di < 0$.

2. Using $\Pi_{ZZ} - C_{ZZ} < 0$, we have $\Pi_Z(z(g), \cdot) - C_Z(z(g), \cdot) \leq \Pi_Z(z(i), \cdot) - C_Z(z(i), \cdot)$ for $i \leq g$. By Lemma 3.A.2, we have $Z_t^R < 0$ for $i < g$ which gives $[\Pi_Z(z(g), \cdot) - C_Z(z(g), \cdot)] \int_0^g Z_t^R di \geq \int_0^g [\mathit{\Pi}_Z - C_Z] Z_t^R di$. In a similar manner, we have $\Pi_Z(z(g), \cdot) - C_Z(z(g), \cdot) \geq \Pi_Z(z(i), \cdot) - C_Z(z(i), \cdot)$ and $Z_t^R > 0$ for $i \geq g$ which implies $[\Pi_Z(z(g), \cdot) - C_Z(z(g), \cdot)] \int_g^n Z_t^R di \geq \int_g^n [\mathit{\Pi}_Z - C_Z] Z_t^R di$, so we have $[\Pi_Z(z(g), \cdot) - C_Z(z(g), \cdot)] \int_0^n Z_t^R di \geq \int_g^n [\mathit{\Pi}_Z - C_Z] Z_t^R di + \int_0^g [\mathit{\Pi}_Z - C_Z] Z_t^R di$.

3. Combining the results from step 1 and 2 we find $\int_g^n [\mathit{\Pi}_Z - C_Z] Z_t^R di + \int_0^g [\mathit{\Pi}_Z - C_Z] Z_t^R di < 0$. Then by (3.A.4) and $e_t < 0$ this implies $t^* < \Delta$. □

Even if, under the lump-sum recycling scheme, a tax increase allows some constrained firms to increase investment, this is no rationale for increasing the emission tax above the marginal emission damages. Even if there exist constrained firms that can increase investment following an increase in t, there are always constrained firms that are forced to reduce their investment due to a tax increase. One can then show that the aggregate cost of this reduction in investment by the latter outweighs the benefits of increased investment opportunities of the former. Low taxes continue to favor constrained firms' investment in general, which implies that the optimal emission tax, t^*, falls short of marginal emission damages, Δ.

3.A.3 Environmental policy and economic shocks

By $T^* = \Delta$, T^* is independent of ξ, a and A. Accordingly, shocks to credit and productivity do not affect the second-period optimal emission tax. The response of t^* to the credit shock is again governed by the investment sensitivity and investment value effects. For the productivity shock, we in addition again identify the emission sensitivity and persistence effects. In Section 3.A.1, we established that, because of the recycling scheme, the tax affects firms $i \in [0, g)$ differently than firms $i \in [g, n]$.

As a consequence, we must now further separate the effects across groups. We first evaluate the response of the optimal first-period tax to a change in ξ. Taking the total derivative of (3.A.4), we find

$$t^*_\xi = B^{-1} \begin{bmatrix} \int_{\min\{n,g\}}^{n} \Big[\underbrace{[\Pi_Z - C_Z]\, Z^R_{t\xi}}_{\substack{\text{investment sensitivity} \\ \text{effect } (+/-)}} + \underbrace{[\Pi_{ZZ} - C_{ZZ}]\, Z^R_\xi Z^R_t}_{\substack{\text{investment value} \\ \text{effect } (-)}} \Big] di \\ + \int_0^{\min\{n,g\}} \Big[\underbrace{[\Pi_Z - C_Z]\, Z^R_{t\xi}}_{\substack{\text{investment sensitivity} \\ \text{effect } (+/-)}} + \underbrace{[\Pi_{ZZ} - C_{ZZ}]\, Z^R_\xi Z^R_t}_{\substack{\text{investment value} \\ \text{effect } (+)}} \Big] di \end{bmatrix}, \tag{3.A.5}$$

with $B > 0$ defined as in the main text. If $g \geq n$, the result collapses to (3.14). Note however that the partial derivatives of Z now include the effect of the shock though the lump sum rebate. For $g < n$, we find that for firms who benefit from tax increases and for firms to whom a marginal tax increase is a net cost, the investment sensitivity effect continues to be ambiguous and may be of opposite signs for both groups. The investment value effect is still positive for the most constrained group, yet turns negative for firms $i \in [g, n]$. This can be explained as follows: an negative shock to credit reduces investment by constrained firms and thereby increases the marginal benefit of investment for these firms. As investment is increasing in the tax for firms $i \in [g, n]$, to benefit from this rise in the return to investment, they call for *higher* taxes following a drop in ξ.

In a similar manner, we evaluate t^*_a. Taking the total derivative of (3.A.4):

$$t^*_a = B^{-1} \begin{bmatrix} \underbrace{(t^* - \Delta) \int_0^1 \frac{e_{ta}}{z} di}_{\substack{\text{emission sensitivity} \\ \text{effect } (+/-)}} \\ + \int_{\min\{n,g\}}^{n} \Big[\underbrace{[\Pi_Z - C_Z]\, Z^R_{ta}}_{\substack{\text{investment sensitivity} \\ \text{effect } (+/-)}} + \underbrace{[\Pi_{ZZ} - C_{ZZ}]\, Z^R_a Z^R_t}_{\substack{\text{investment value} \\ \text{effect } (-)}} + \underbrace{\mu \Pi_{ZA} Z^R_t}_{\substack{\text{persistence} \\ \text{effect } (+)}} \Big] di \\ + \int_0^{\min\{n,g\}} \Big[\underbrace{[\Pi_Z - C_Z]\, Z^R_{ta}}_{\substack{\text{investment sensitivity} \\ \text{effect } (+/-)}} + \underbrace{[\Pi_{ZZ} - C_{ZZ}]\, Z^R_a Z^R_t}_{\substack{\text{investment value} \\ \text{effect } (+)}} + \underbrace{\mu \Pi_{ZA} Z^R_t}_{\substack{\text{persistence} \\ \text{effect } (-)}} \Big] di \end{bmatrix}. \tag{3.A.6}$$

Again, if $g \geq n$, the result collapses to (3.11). The investment sensitivity effect continues to be ambiguous and may be of opposite signs for both groups. As above, the fact that higher taxes increase investment for firms $i \in [g, n]$ while reducing it for firms $i \in [0, g]$, is the reason behind the opposite signs of the investment value effect across groups. The same mechanism causes the signs of the persistence effect to be opposite. A drop in A reduces the benefit of investment and thus allow for a fall in investment in the optimum. For firms $i \in [0, g]$, this fall is accomplished by an increase in the tax, for firms $i \in [g, n]$ this calls for a reduction in t. As in the main text, both t_ξ^* and t_a^* are ambiguous without further functional specification.

3.A.4 Example: specific functional form

If we adopt the specific functional forms from Section 3.6, we again arrive at unambiguous results for the signs of t_ξ^* and t_a^*. As before, both t_ξ^* and t_a^* are positive; Propositions 3.4 and 3.5 continue to hold. Although not formally proven below, also for the individual effects, all signs carry over for $i \in [0, g)$. For $i \in [g, n]$, signs are opposite.

We use (3.18) and (3.20), to reduce (3.A.5) to[29]

$$t_\xi^* = [\gamma \xi B]^{-1} \begin{bmatrix} \int_{\min\{n,g\}}^{n} Z_t^R \left[T M_Z - \gamma C_Z \right] di \\ + \int_0^{\min\{n,g\}} Z_t^R \left[T M_Z - \gamma C_Z \right] di \end{bmatrix}, \tag{3.A.7}$$

and we can re-establish Proposition 3.4:

Proposition 3.A.2. *Under specifications (3.17)-(3.18), as long as some firms are constrained, the optimal first-period tax falls in response to an adverse credit shock.*

Proof. First of all, from the proof of Proposition 3.A.1, we know $\int_0^1 Z_t^R di < 0$ with $\int_0^g Z_t^R di < 0$ and $\int_g^n Z_t^R di > 0$. Now, if M_Z is smaller (more negative) for low z firms, we must have that $T \int_0^n Z_t^R M_Z di > 0$. Since we have $M_{ZZ} = Z^{-1} \left[E_{ZZ} - 2M_Z \right] > 0$, by $E_{ZZ} > 0$ and $Z_z^R > 0$, this is indeed the case. Also, we know $C_Z Z_t^R = \xi \left[\pi_t + s_t \right]$, which gives $\int_0^n C_Z Z_t^R di = \xi \int_0^n \left[\pi_t + s_t \right] di < 0$ This implies we must have $t_\xi^* > 0$. □

Following the same procedure as for the credit shock, we use (3.18), (3.20) and (3.A.6) to find[30]

$$t_a^* = [\gamma B]^{-1} \begin{bmatrix} \int_{\min\{n,g\}}^{n} \left[\gamma \Pi_Z (\mu - 1) + T M_Z \right] Z_t^R di \\ + \int_0^{\min\{n,g\}} \left[\gamma \Pi_Z (\mu - 1) + T M_Z \right] Z_t^R di \end{bmatrix}. \tag{3.A.8}$$

This allows us to prove the following:

Proposition 3.A.3. *Under specifications (3.17)-(3.18), as long as some firms are constrained, the optimal first-period tax falls in response to an adverse productivity shock.*

Proof. First, we know $M_Z = Z^{-2} \left[Z E_Z - E \right] < 0$ and $M_{ZZ} = Z^{-1} \left[E_{ZZ} - 2M_Z \right]$. We have $E_{ZZ} > 0$, which implies $M_{ZZ} > 0$. Hence, $T \int_0^n Z_t^R M_Z di > 0$. Next, we have

[29] For the details, see the proof to Proposition 3.4.

[30] For the details, see the proof to Proposition 3.5.

$\Pi_Z = TMZ^{-1} > 0$ and $\Pi_{ZZ} = Z^{-2}T\left[ZM_Z - M\right] < 0$. Hence, $\int_0^n \Pi_Z Z_t^R < 0$. By $\mu \leq 1$, we must thus have $t_a^* > 0$. $\square$

3.B Notation and signs of derivatives

The tables below present an overview of the model variables and the signs of derivatives of the model laid out in Section 3.2 and solved in Section 3.3. Note that still, lower case letters refer to first-period variables while upper case letters denote second-period variables, and the *i*indicates that we are dealing with firm-specific variables.

Table 3.B.1: Model variables

$y(.)$, $Y(.)$	Output
$e(.)$, $E(.)$	Energy use
$m(.)$, $M(.)$	Emissions
q, Q	Energy price
$z(i)$, $Z(i)$	Energy emission intensity
$\pi(.)$, $\Pi(.)$	Profit
$C(.)$	Investment cost
t, T	Emission tax
a, A	Productivity
ξ	Credit parameter
μ	Productivity shock persistence

Table 3.B.2: Model derivatives

Derivative	Sign	Derivative	Sign	Derivative	Sign
y_a, Y_A	> 0	C_z	≤ 0	Z_z^U	≥ 0
y_e, Y_E	> 0	C_Z	> 0	Z_t^U	$= 0$
y_{ee}, Y_{EE}	< 0	C_{ZZ}	> 0	Z_T^U	> 0
y_{ea}, Y_{EA}	> 0				
				Z_z^R	> 0
e_t, E_T	< 0	π_z, Π_Z	> 0	Z_t^R	< 0
e_{ta}, E_{TA}	ambiguous, see (3.16)	π_{zz}, Π_{ZZ}	< 0	$Z_{t\xi}^R$	ambiguous, see (3.12)
		π_{za}, Π_{ZA}	> 0	Z_{ta}^R	ambiguous, see (3.15)
m_z, M_Z	< 0	π_t, Π_T	< 0	Z_T^R	$= 0$
m_t, M_T	< 0			Z_ξ^R	> 0
				Z_a^R	> 0

Note that except for $Z_{t\xi}^R$ and Z_{ta}^R, the second-period derivatives are listed here are partial effects; they take Z as given.

Chapter 4

TOO SLOW A CHANGE? DEEP HABITS, CONSUMPTION SHIFTS AND TRANSITORY TAX POLICY

Abstract

Resource scarcity, collapsing fish stock and environmental externalities all call for a shift in the goods we consume. This chapter studies the optimal transition towards a new consumption bundle if consumption is subject to good-specific, or 'deep', habits and consumers do not internalize the habit formation process. Habits play two roles. First, they cause persistence in good-specific consumption and thereby slow down shifts in consumption. Second, at the aggregate level, habits act as benchmark against which consumption is evaluated and thereby negatively affect welfare. I establish that a more rapid transition is welfare-improving if the persistence effect is relatively strong. If instead the welfare effect dominates, the optimal transition to a new consumption bundle is slow. The corresponding optimal path of taxes or subsidies then depends on whether goods are produced competitively or monopolistically. I apply the model to water use reductions in California and find a transitory subsidy of up to 60 percent of the shift in prices required to achieve long-run reduction goals. The mandate implemented by the Californian government increases the cost of transitioning away from water consumption by 6 percent.

4.1 Introduction

A rapidly expanding literature in behavioral economics documents how consumer preferences and rationality deviate from 'standard' neoclassical assumptions (DellaVigna, 2009; Rabin, 2002; Samson, 2014; Tirole, 2002). Preferences for instance, are shaped by context and reference points. I consider the specific case of habit formation, where utility from consumption depends on habits (Frederick and Loewenstein, 1999; Rabin, 2002). As habits only slowly catch up with actual consumption, consumption patterns become persistent. People however have difficulty anticipating such future preference changes. This is known as projection bias, and implies individuals do not appropriately internalize the effect of current consumption decisions on future demand and welfare (DellaVigna, 2009; Frederick and Loewenstein, 1999; Loewenstein et al., 2003). Against this backdrop, a question arises whether fiscal policies can improve welfare by correcting this habit internality. This question has relevance especially where policymakers foresee or manage a change in consumption patterns.

Several imminent changes in consumption patterns can be identified across the globe. In 2014, droughts and water shortages were reported from Australia to California and Tehran to Sao Paulo. Many of these areas have a long history with droughts. Yet, more intensive agriculture and population growth increase the difficulty of dealing with ensuing water shortages. In California for instance, water shortages have led farmers to rely more on the already dwindling groundwater stock and reservoir water levels have fallen below 60 percent of average levels (New York Times, 2015; State of California, 2015a). Combating water shortages and preventing an irreversible depletion of groundwater resources will require a substantial reduction in water use by the agricultural sector and households.

Collapsing ocean fish stock will force consumers to shift their diets away from the most-prized species. The most telling example concerns bluefin tuna. Bluefin tuna is a highly migratory fish species that is caught across the world's major oceans. It is also one of the largest fish species; a fully-grown tuna can weigh more than 500 kg. Japan is the largest market for bluefin, consuming about 80 percent of the global catch. Bluefin tuna is however also a critically endangered species (IUCN, 2015). To prevent species extinction, fishing quota need to be lowered and more strictly enforced, and consumption needs to fall.

Similar examples can be found in other areas. For instance, congestion and more stringent local pollution policies will require urbanites to abandon their gas-guzzling vehicle for a more efficient one, shift to public transport or even a bicycle. Stringent climate policies can contribute to this trend, and bring an end to an era of cheap energy.

When habits cause consumption persistence, such a shift in consumption patterns will not come about from one day to another. Rather, consumption, and habits, will only gradually adjust. In this context, the question is whether from a welfare perspective, this shift is too slow, or still too fast. Put differently, is a policy that further smooths this change in consumption welfare-improving, or should policy be used to implement a faster transition?

In this chapter, I answer this question. I put forward a simple model of habit formation. In this model, a representative consumer forms habits at the level of individual goods. These good-specific habits cause persistence in consumption patterns. At the aggregate level, habits form a benchmark against which consumption is evaluated. This benchmark, which slowly adjust to consumption, causes any increase in utility due to an increase in the consumption level to fade over time; as the consumer get used to a higher consumption level she loses (part of) her appreciation for it. The consumer does not internalize that current consumption affects future habits and thereby future demand and welfare. Consumption decisions may therefore deviate from the optimal path, which is defined as the path that maximizes welfare, taking into account the endogenous formation of habits.

As all goods are subject to habits, habits provide no reason to subsidize consumption of one good relative to another in steady state. However, habits do affect the optimal adjustment path of consumption towards a new bundle. This optimal transition is faster the stronger are habits at the good-specific level vis-a-vis the aggregate level. At the good-specific level, the consumer prefers to consume goods she has a high habit in. As a consequence, as she does not internalize that current consumption affects future habits, she keeps 'too high' habits in the goods consumption shifts away from. Inducing the consumer to speed up the transition thus improves welfare. At the aggregate level however, the transition offers an opportunity to manage the habit benchmark against which consumption is evaluated. A slow transition, which implies the consumer consumes to a relatively 'inefficient' bundle for a longer period of time, pulls down this benchmark most. This in turn brings about welfare gains.

The optimal consumption path can be implemented by temporary, or transitory, fiscal policy. A positive tax on goods consumption shift away from speeds up the transition, while a subsidy slows it down. The exact path of taxes and subsidies then depends on whether goods are produced under monopolistic or perfect competition. Under monopolistic competition, forward-looking producers invest in habits. An anticipated drop in demand reduces the value of this investment, and increases the markup charged by monopolists. This price response speeds up the transition to the new consumption bundle compared to the competitive market. Hence, I find that transitory subsidies are always required to implement the optimal consumption tax under monopolistic competition, while taxes may still be called for under perfect competition.

To illustrate the mechanisms and quantify effects, I apply the framework to the water use restrictions recently imposed in California. Here, I determine the optimal path away from water consumption, such that water use falls by 25 percent in the long run. I find the optimal transition to be relatively slow; water use drops by 10 percent at the onset of the shift, and it takes more than 10 years before the remaining 15 percent reduction is met. Implementing this path requires sizeable policy intervention; initial subsidies are 37 to 57 percent of the increase in water prices required to achieve the 25 percent long run reduction. Appropriately managing this transition brings about sizeable welfare gains; the Californian mandate, which required *immediate* water savings of 25 percent, increased welfare losses along the transition by 6 percent. The mandate had the advantage of being simple and straightforward to implement. I propose two alternative simple policy rules which generate a welfare levels close to the one under the optimal path.

The remainder of this chapter is structured as follows. Section 4.2 discusses the relevant literature. The model is introduced in Section 4.3. Section 4.4 discusses the equilibrium, and Section 4.5 presents the transition path in response to a one-off increase in unit production cost in the absence of additional policy intervention. Optimal policy is evaluated in Section 4.6. The model is calibrated in Section 4.7. Section 4.8 concludes. Detailed derivations and proofs can be found in Appendices 4.A through 4.C.

4.2 Literature

Early theoretical contributions on habit formation have been made by Pollak (1970), Ryder and Heal (1973), Becker and Murphy (1988) and Abel (1990). The work by Pollak (1970), and later Carroll (2000) and Hiraguchi (2008), focuses on the properties of demand functions with habit formation. The implications of habit formation have been explored in fields as diverse as asset pricing (Abel, 1990; Campbell and Cochrane, 1999; Constantinides, 1990), growth (Alonso-Carrera et al., 2005; Alvarez-Cuadrado et al., 2004; Carroll et al., 2000; Monteiro et al., 2013; Ryder and Heal, 1973; Turnovsky and Monteiro, 2007), addiction (Becker and Murphy, 1988), life cycle consumption and savings (Cremer et al., 2010; Koehne and Kuhn, 2015) and the relationship between income and happiness (Choudhary et al., 2012; Layard, 2006). In these fields, habits have been put forward as an explanation for multiple 'puzzles', such as the equity premium puzzle (Abel, 1990; Campbell and Cochrane, 1999; Constantinides, 1990), the observation that growth Granger causes savings (Carroll and Weil, 1994; Carroll et al., 2000) and the Easterlin paradox (Choudhary et al., 2012). Including habits in monetary policy and DSGE models allows these models to capture certain features of the macroeconomy, such as the gradual response of real spending to shocks (Fuhrer, 2000) and counter-cyclical markups (Ravn et al., 2006). Also empirical research generally confirms the presence of habit formation in consumption. Bronnenberg et al. (2012) for instance, find that endogenous brand preferences explain 40 percent of the geographic variation in market shares. Carrasco et al. (2005) test for habits formation in food, services and transport. They find evidence for habits in food and services; accounting for individual fixed effects, a 1 percent increase in past consumptions of food and services increases current consumption by 0.72 and 0.14 percent respectively.[1]

Empirical evidence from the fields of psychology and behavioral economics indicates that consumers are not fully rational with respect to observing and anticipating the habit formation process. Instead, individuals suffer from projection bias, i.e. they fail to fully anticipate preference shifts (Conlin et al., 2007; Frederick and Loewenstein, 1999; Loewenstein et al., 2003).[2] This opens up room for welfare-improving policy intervention. Ljungqvist and Uhlig (2000) for instance, show that habits provide a rationale for procyclical taxes, as such taxes counter the tendency to build up ’too high’ habits during booms. In the context of growth, Alonso-Carrera et al. (2005) characterize the income and consumption tax rates that implement the optimal path of consumption as the economy transitions to the balanced growth path. In Cremer et al.’s (2010) two-period model with retirement, habit formation and myopia cause overconsumption and undersaving in the first period of life. A tax on first-period consumption and a lump-sum transfers then implements the first-best allocation. If lump-sum transfers are infeasible, the second-best policy will also have redistributive implications.

This chapter contributes to this literature, which evaluates the implications of habit formation for optimal (tax) policy when consumers do not fully internalize the habit formation process.[3] With the exception of the work by Ravn et al. (2006),

[1] See also Dynan (2000), Ravina (2005), Dubé et al. (2010), Alvarez-Cuadrado et al. (2012), Atkin (2013) and Verhelst and Van den Poel (2014). All except Dynan (2000) find evidence for habit formation. This literature is discussed in more detail in Section 4.7.

[2] Projection bias blurs the distinction between habit formation when habits are formed internally and own past consumption acts as a ’reference point’, or externally, where the reference point depends on past consumption of a peer group (also known as ’catching up with the Joneses’). In both cases, external habits and internal habits with projection bias, the consumer does not internalize the habit formation process. For this reason, both the literature on, and policy implications of, internal and external habit formation are relevant to this chapter. See also Section 4.3.

[3] More generally, I contribute to a broader literature in ’behavioral public economics’, which evalu-

the theoretical research cited above assumes habits form at the level of aggregate consumption instead of individual goods. Hence, this research cannot address the implications of habit formation for shifts *within* the consumption bundle. To my knowledge, I am the first to evaluate the potential policy implications of habit formation when habits are formed at the good-specific level. The distinction between aggregate (superficial) and good-specific (deep) habits was first made by Ravn et al. (2006). When habits form at the level of individual goods, strategic behavior by firms becomes relevant; a central result of Ravn et al. (2006) is that deep habits give rise to countercyclical markup behavior. In Ravn et al. (2010), the authors more closely assess the pass-through of marginal cost shocks and establish that pass-through is increasing in the persistence of cost shocks, and may even exceed a 100 percent. Such 'excessive' pass-through is also a feature of my setup, and will tend to speed up shifts within the consumption bundle.

The deep habits specifications formulated by Ravn et al. (2006), and further used by Doi and Mino (2008), Ravn et al. (2010) and Nakamura and Steinsson (2011), do not separate the two effects of habit formation; the presence of good-specific habits always reduces (steady-state) welfare whenever habits lead to persistence in consumption, and vice versa. I propose a specification that separates these two effects. This allows me to more closely evaluate the importance of these effects and their relative strength in determining the optimal adjustment path of consumption.

As argued in the introduction, consumption patterns can change for many reasons. Several of those reasons relate to resource scarcity and environmental externalities. In this context, this chapter contributes to a more specialized literature that assesses the optimal time path of environmental taxes, and carbon taxes in particular. In this literature, numerous rationales for time-varying taxes have been proposed, ranging from innovation externalities (Acemoglu et al., 2012; Gerlagh et al., 2009) to issues related to resource scarcity and the so-called green paradox (Sinn, 2008; Ulph and Ulph, 1994). Here, this chapter provides an additional, previously uninvestigated, rationale for time-varying environmental taxes: habits.

4.3 Model

I consider a simple setup where a representative consumer consumes a variety of goods i, with $i \in [0, 1]$ and t denotes time. The consumer forms habits $h_i(t)$ over the

ates the policy implications of non-standard (behavioral) assumptions. Examples of such behavioral assumptions include projection bias considered here, but also hyperbolic discounting, reference-dependent preferences, overconfidence, and limited attention (DellaVigna, 2009). See for instance O'Donoghue and Rabin (2006) for optimal policy under hyperbolic discounting and Bernheim and Rangel (2007) and Dalton and Ghosal (2011) for a general discussion.

same varieties. These good-specific, or 'deep', habits cause persistence in consumption decisions: demand for good i, $c_i(t)$, is increasing in habit $h_i(t)$. Consumption and habits are aggregated into $C(t)$ and $H(t)$. The representative consumer's instantaneous utility $U(t)$ at time t increases in effective consumption $C(t)$, and $C(t)$ relative to a benchmark, the aggregate habit $H(t)$. The higher this benchmark, the lower is utility from consumption. Hence, the aggregate habit causes some degree of hedonic adaptation: the utility gain from a permanent increase in consumption (partly) fades out over time as consumers become accustomed to the higher consumption level.[4] Note that in the remainder, I omit time from notation when convenient.

Instantaneous utility reads

$$U(t) = \frac{\left(C(t)^{1-\gamma}\left(\frac{C(t)}{H(t)}\right)^{\gamma}\right)^{1-\sigma}}{1-\sigma}, \tag{4.1}$$

where $\sigma > 0$ is the (negative) elasticity of marginal utility when habits are exogenous. The parameter γ is the aggregate habit strength, and measures the importance of the aggregate habit benchmark in utility. Here I set $\gamma \in [0,1]$. Effective consumption is an aggregate of consumption over a variety of goods c_i. The importance of each variety in C depends on (endogenous) good-specific consumption weights w_i. These weights in turn depend on habits; a higher good-specific habit relative to the aggregate habit increases the weight of a good i in C:

$$C(t) = \left[\int_0^1 w_i(t) c_i(t)^{\frac{\eta-1}{\eta}} di\right]^{\frac{\eta}{\eta-1}}, \tag{4.2}$$

and

$$w_i(t) = \left(\frac{h_i(t)}{H(t)}\right)^{\frac{\theta}{\eta}}. \tag{4.3}$$

Here, η is the instantaneous elasticity of substitution across varieties and $\theta \in [0,1)$ is the good-specific habit strength. Deep habits, at the level of individual varieties, increase demand for specific varieties as they increase these varieties' weight in the consumption aggregate. Note that the aggregation from c_i to C preserves linear homogeneity: a proportional increase in all c_i translates into an equiproportional increase in C. The aggregate habit is a measure for the effective consumption level the

[4]The hedonic treadmill, or hedonic adaptation, is a concept from psychology which describes the tendency for humans to quickly return to a relatively stable level of happiness following a major positive or negative life event (Frederick and Loewenstein, 1999).

consumer is accustomed to and defined as follows

$$H(t) = \left[\int_0^1 w_i(t) h_i(t)^{\frac{\eta-1}{\eta}} di \right]^{\frac{\eta}{\eta-1}} . \tag{4.4}$$

H is linearly homogeneous in good-specific habits h_i which implies consumption weights are independent of the scaling of the habit. A proportional increase in all habits h_i thus reduces utility only through an increase the aggregate habit benchmark H; it does not alter effective consumption C. Similarly, a shift in good-specific habits, keeping the aggregate habit H constant, only affects utility through its effect on the good-specific consumption weights w_i and effective consumption C. Such a shift in good-specific habits will increase effective consumption C if it brings the pattern of habits more in line with the pattern of consumption.[5] If consumption and habits are uniform across all varieties, we have $H = h_i$, $w_i = 1$ and $C = c_i$.

Good-specific habits slowly catch up with consumption:

$$\dot{h}_i(t) = \xi \left(c_i(t) - h_i(t) \right), \tag{4.5}$$

where the dot denotes a time derivative and $\xi > 0$ is the adjustment speed of the habit. In steady-state, habits have converged to actual consumption: $h_i = c_i$. From (4.2) and (4.4) it then also follows that in steady state, the aggregate habit equals effective consumption: $H = C$.

The specification above allows me to clearly disentangle two effects of habits. First, θ measures the degree to which habits cause persistence in consumption decisions. The higher is θ, the more responsive is the consumption weight w_i to a change in good-specific habits h_i. Then, as will become clear in the next section, a higher θ implies greater persistence in consumption patterns. If $\theta = 0$, consumption choices are independent of good-specific habits, and (4.2) collapses to the standard Dixit-Stiglitz specification. Second, γ measures the degree to which, over time, consumers adapt to changes in effective consumption C. The higher is γ, the more important is the aggregate habit benchmark in welfare. If $\gamma = 1$, changes in consumption do not lead to long-term utility gains or losses. With $\gamma = 0$, aggregate habits do not affect utility from C.

For production, I assume a constant returns to scale production technology, where the production of each good requires $\delta_i > 0$ units of labor. Total labor supply,

[5] This could be illustrated by the following example. Consider a consumption bundle that is high in vegetables and low in meat. Then effective consumption C derived from this bundle is higher if the consumer is used to this high vegetable, low meat diet, than if she were used to a low vegetable, high meat diet. Both diet habits however, could resemble the same standard of living, i.e. the same H.

L, is fixed, so that the labor market equilibrium reads as follows

$$L = \int_0^1 \delta_i(t)c_i(t)di. \tag{4.6}$$

In addition to the direct labor cost of production, producers may face a good-specific production tax. I normalize the wage rate to unity. To the producer, the total cost of producing one unit of c_i then equals $\delta_i(t)\tau_i(t)$ where $\tau_i(t)$ is the gross tax rate; for $\tau_i(t) > 1$, good i production is subject to a positive tax, and good i is subsidized if $\tau_i(t) < 1$.

Production cost δ_i may shift for a number of reasons. In the context of the examples discussed in the introduction, δ_i may increase due to the implementation of stricter regulation regarding water use and extraction. Similarly, the introduction of stringent climate policy will increase production costs for carbon-intensive goods.[6] Higher production costs for a subset of goods will induce the consumer to, over time, substitute away from these goods. The relevant policy question is then how the policymaker can use taxes τ_i to optimally manage the speed at which this transition takes place.

In the remainder, I assume that the representative consumer and producers discount future utility and profits at the same rate $\rho > 0$, and any positive tax revenues are rebated lump sum. Finally, I make two additional assumptions regarding the rationality of the consumer and producers:

Assumption 4.1. The representative consumer is subject to strong projection bias, i.e. it does not internalize the effect of current consumption on future habits.

Projection bias is a form of limited rationality where individuals do not (fully) anticipate future changes in preferences (Loewenstein et al., 2003; Samson, 2014). As a consequence, in the face of changing preferences, the individual is unable to fully optimize its consumption decisions. In our context, this implies that demand is a function of the goods' current prices and habits, but not on expected future prices.

Assumption 4.2. Producers are forward-looking and atomistic.

[6]The framework currently abstracts from the source of the increase in δ_i and thus implicitly assumes that any change in δ_i is exogenous to the model. Expression (4.6) can however easily be adapted to explicitly account for the presence of a negative (environmental) externality due to the production of one or some goods. Suppose we have two types of goods, c_{i1} and c_{i2}, both with unit labor requirement 1, and good c_{i1} has a negative external effect on overall labor productivity such that (4.6) is replaced by $(1 - \delta_1' c_{i1})\, L = \int_0^1 c_i di$ where δ_1' is the externality of c_{i1} production. One can then show that an optimal policy can be decomposed into two taxes. First, a tax equal to δ_1' on the production of c_{i1} to ensure c_{i1} producers internalize the negative external effect of production on overall labor productivity. Second, taxes τ_i to manage the speed at which consumption substitutes away from c_{i1}, as discussed in the remainder of this chapter. More details are available upon request.

Contrary to the consumer, producers do anticipate that current consumption affects future demand through habits. Hence, they adjust their optimization accordingly. Their atomistic size however implies that even though producers internalize the direct effect of $c_i(t)$ on the evolution of the good-specific habit $h_i(t)$, they do not internalize the subsequent effect on the aggregate habit $H(t)$.[7] As we will see below, habits affect the price charged by monopolistic firms. If markets are perfectly competitive, goods are always sold at marginal costs.

Catching up with the Joneses Equivalent to Assumption 4.1 is assuming 'catching up with the Joneses' as in Abel (1990), Alvarez-Cuadrado et al. (2004) and Alonso-Carrera et al. (2005). In such a setup, $h_i(t)$ represents an external habit, or reference point based on (past) consumption in the peer group. To the individual consumer, this habit is exogenous. With a representative consumer, h_i then still evolves according to (4.5).[8] In the remainder of the chapter, I continue to interpret h_i as an internal habit where the consumer does not internalize the habit formation process. All results and policy recommendations continue to apply if habits are formed externally as described above.

4.4 Equilibrium

The representative consumer maximizes instantaneous utility while taking habits as given. Income equals expenditures $PC = L$. This gives demand

$$c_i = \left(\frac{p_i}{P}\right)^{-\eta} \left(\frac{h_i}{H}\right)^{\theta} \frac{L}{P}, \tag{4.7}$$

where p_i is the price of good i and

$$P = \left[\int_0^1 \left(\frac{h_i}{H}\right)^{\theta} p_i^{1-\eta} di\right]^{\frac{1}{1-\eta}} \tag{4.8}$$

is the price of effective consumption. Demand for good i decreases in the price of good i relative to the price index P and increases in real income L/P. For given ag-

[7]This implication is akin to the notion that monopolistically competitive firms internalize the effect of own output on the good-specific price, but not on the aggregate price level in the economy.

[8]More specifically, let j be the indicator for the consumer, such that $c_{ji}(t)$ is the time t good i consumption of individual $j \in [0,1]$. Then (4.2) can be rephrased as $C_j(t) = \left[\int_0^1 w_i(t) c_{ji}(t)^{\frac{\eta-1}{\eta}} di\right]^{\frac{\eta}{\eta-1}}$. (4.3)-(4.5) still apply, where in (4.5) c_i is now defined as $c_i(t) = \int_0^1 c_{ji}(t) dj$. With a representative consumer, $C_j(t)$ then collapses to $C(t)$ as in (4.2).

gregate habit H, a higher good-specific habit h_i increases the weight of consumption c_i in C. As a consequence, demand increases in the good-specific habit. This in turn also increases the weight of the good i price in the price aggregate P. On the producer side, price-setting is straightforward if markets are perfectly competitive. In this case we have

$$p_i(t) = \delta_i(t)\tau_i(t). \tag{4.9}$$

Under monopolistic competition, producers choose a series of prices that maximizes the time t present value of profits $\Pi_i(t) = \int_t^\infty e^{-\rho(\nu-t)} c_i(\nu)\left[p_i(\nu) - \delta_i(\nu)\tau_i(\nu)\right] d\nu$, where c_i is given by (4.7). Producers anticipate that a reduction in the current prices does not only increase current sales, but also, through habits, future demand and profits. Setting a low price to build habit can thus be viewed as an investment in future profits. Hence, habits are expected to reduce markups, which is confirmed by the following result for the monopolist pricing rule:[9]

$$p_i = \frac{\eta}{\eta - 1}\left[\delta_i(t)\tau_i(t) - \xi\kappa_{h_i}(t)\right], \tag{4.10}$$

where

$$\kappa_{h_i}(t) = \int_t^\infty e^{-(\rho+\xi)(\nu-t)} \frac{\theta}{\eta} \frac{c_i(\nu)}{h_i(\nu)} p_i(\nu)\, d\nu, \tag{4.11}$$

and I require $\eta > 1$ to ensure positive markups. The standard monopoly pricing rule now includes a habit discount, $\xi\kappa_{h_i}$. The size of this discount depends on the shadow value of the habit to the monopolist, κ_{h_i}, multiplied by the direct effect of an increase in consumption on the future habit, ξ. The monopolist sets a low price if investing in the habit is valuable, i.e. if the shadow value of the habit is high. This is the case if (future) demand is very sensitive to the habit (high $\theta c_i/h_i$) and prices are high (high p_i). A low elasticity of substitution η then implies markups are high, and a large share of this price constitute pure profits. Future returns are discounted at a rate $\rho + \xi$, where a higher discount rate reduces the shadow value of the habit. This is due to the fact that a low persistence of the habit (high ξ) reduces the marginal effect of an increase in c_i today on habits further in the future, while stronger time preference (high ρ) reduce the present value of a given flow of returns.

Habits do not only lead to lower markups, but also to time-varying markups. This can be seen as follows. Suppose that p_i is constant, and we initially have $h_i < c_i$. Then as habits catch up with consumption, c_i/h_i falls and so does the shadow value of the habit. This increases the monopolist's price according to (4.10) and is thus inconsistent with the constant price just assumed.

[9]See Appendix 4.A for detailed derivations.

4.4.1 Steady state

The economy is in steady state if prices, consumption and habits are constant over time. Then, by (4.5), for all goods $i \in [0,1]$, habits must equal consumption: $c_i^* = h_i^*$. Here, the star indicates we are in steady state. Then by (4.2) and (4.4) it follows that in steady state also the aggregate habit equals effective consumption: $C^* = H^*$. Then, the good i steady-state price under perfect competition equals

$$p_i^* = \delta_i \tau_i^*. \tag{4.12}$$

To the monopolist, the steady-state shadow value of the habit is

$$\kappa_{h_i}^* = \frac{1}{\rho + \xi} \frac{\theta}{\eta} p_i^*, \tag{4.13}$$

which with (4.10) gives the following steady state price:

$$p_i^* = \delta_i^* \tau_i^* \frac{\eta}{\eta - 1} \left[\frac{\rho + \xi}{\rho + \xi \left(1 + \frac{\theta}{\eta - 1}\right)} \right]. \tag{4.14}$$

Even though habits reduce the monopoly markup in steady state, it remains positive.[10] As I abstract from saving and assume labor supply is fixed, consumption decisions are fully determined by *relative* prices. In the remainder of the chapter, for ease of exposition, I consider the case where goods can be divided in two types, a and b. Unit production costs for these types are then δ_{ia} and δ_{ib} respectively.[11] From (4.7) steady-state relative consumption then equals

$$c^{R*} = \left(p^{R*}\right)^{-\frac{\eta}{1-\theta}}, \tag{4.15}$$

with $c^R \equiv c_{ia}/c_{ib}$ and $p^R \equiv p_{ia}/p_{ib}$. The steady-state relative price is independent of market structure:

$$p^{R*} = \delta^{R*} \tau^{R*}, \tag{4.16}$$

[10] The monopoly markup is positive if $\frac{\eta}{\eta-1} \frac{\rho+\xi}{\rho+\xi\left(1+\frac{\theta}{\eta-1}\right)} > 1$. This condition can be rearranged to $\rho > \xi(\theta - 1)$.

[11] All results generalize to the case with any number of good types and corresponding unit production costs. Details are available upon request.

where δ^R and τ^R are defined in line with c^R and p^R. Then by (4.6) I arrive at the following solution for steady-state consumption of type a and b goods:

$$\begin{aligned} c_{ia}^{*} &= c^{R*}\left[n\delta_{ia}^{*}c^{R*}+(1-n)\,\delta_{ib}^{*}\right]^{-1}L; \\ c_{ib}^{*} &= \left[n\delta_{ia}^{*}c^{R*}+(1-n)\,\delta_{ib}^{*}\right]^{-1}L, \end{aligned} \tag{4.17}$$

where n is the share of a-goods. Then, I find

$$C^{*}=\frac{\left[n\left(c^{R*}\right)^{\frac{\eta-1+\theta}{\eta}}+(1-n)\right]^{\frac{\eta}{\eta-1+\theta}}}{n\delta_{ia}^{*}c^{R*}+(1-n)\,\delta_{ib}^{*}}L, \tag{4.18}$$

and

$$U^{*}=\frac{\left(C^{*}\right)^{(1-\gamma)(1-\sigma)}}{1-\sigma}. \tag{4.19}$$

The steady-state is interior and unique only if demand is strictly concave in the good-specific habit, i.e. only if $\theta < 1$. This condition is easily derived from (4.7). For a given set of prices, consumption scales with the habit at degree θ. Then if relative consumption, c^R, rises by 1 percent, future habits follow, and in turn future relative consumption goes up by an additional θ percent. The long run increase in c^R is then bounded only if $\theta < 1$.

This observation is mirrored in our result for the long run price elasticity of demand. With good-specific habit formation, the long run price elasticity of demand exceeds the short run one. This can be seen by comparing expressions (4.7) and (4.15). From (4.7), the (absolute value of) the short run price elasticity of demand is equal to the instantaneous elasticity of substitution across goods: $\varepsilon_p^{SR} = \eta$. In the long run, this price elasticity of (relative) demand is $\varepsilon_p^{LR} = \eta / (1-\theta)$ (see (4.15)). In the absence of good-specific persistence ($\theta = 0$) these elasticities are equal. For positive θ, the long run shift in consumption in response to a change in relative prices exceeds the short run one: $\varepsilon_p^{LR} > \varepsilon_p^{SR}$. If $\theta = 1$, ε_p^{LR} is unbounded, indicating that, in the long run, goods act as perfect substitutes. As a consequence, not all goods may be consumed in steady state. Which particular equilibrium consumption would settle upon however, depends on initial values of the h_i. As stated in Section 4.3, I assume $\theta \in [0, 1)$, which rules out such indeterminacy.

A change in the steady-state C will only affect steady-state utility if the aggregate habit strength, γ, is unequel to 1 (see (4.19)). If $\gamma = 0$, aggregate habits do not affect utility for a given level of effective consumption C. If $\gamma = 1$, utility only depends on the level of effective consumption relative to the habit: C/H. As habits catch up with consumption, welfare will always return to a stable long-run level.

Finally, in steady state, due to uniform markups, the relative price p^R is independent of whether goods are produced under perfect or monopolistic competition. Outside of steady state however, the relative price set under monopolistic competition diverges from the perfect competition price ratio (see (4.9) and (4.10)). As will be shown in Section 4.5, this gives two distinct transition paths of consumption towards a steady-state equilibrium.

4.4.2 Transition

With habit formation, consumption need not always be in steady state. When consumption lies above or falls short of the habit, the habit will change over time, affecting future demand and possibly prices. In this subsection, I provide a general characterization of the paths of consumption, prices and habits as the economy converges to the steady state. In Section 4.5 I use this characterization to evaluate changes in consumption in response to a permanent change in unit production costs. Section 4.6 evaluates the optimal path, and characterizes the policy required to implement it.

To approximate the path of consumption and prices I loglinearize the system around its steady state. Let a tilde denote a log-deviation from the steady-state, such that $\tilde{z}(t) \equiv dz(t)/z^* \approx (z(t) - z^*)/z^*$ and thus $\tilde{z}^R = \tilde{z}_{ia} - \tilde{z}_{ib}$ for some variable z. The loglinearized the demand equation (4.7) then reads

$$\tilde{c}^R(t) = -\eta \tilde{p}^R(t) + \theta \tilde{h}^R(t). \tag{4.20}$$

From (4.5), $\tilde{h}^R(t)$ evolves according to

$$\dot{\tilde{h}}^R(t) = -\xi \lambda \tilde{h}^R(t), \tag{4.21}$$

where I define the following linear relationship between $\tilde{c}^R(t)$ and $\tilde{h}^R(t)$:[12]

$$\lambda \equiv 1 - \tilde{c}^R(t)/\tilde{h}^R(t). \tag{4.22}$$

Then (4.20)-(4.22) give the following solutions for the evolution of relative consumption, prices and habits:

$$\tilde{c}^R(t) = [1 - \lambda] \tilde{h}^R(t); \tag{4.23}$$

[12] For ease of exposition, I already implicitly assume λ is constant. In Sections 4.5 and 4.6 I use loglinearized pricing rules to determine λ and find that λ is indeed constant.

$$\tilde{p}^R(t) = \left[\frac{\theta - 1 + \lambda}{\eta}\right] \tilde{h}^R(t); \tag{4.24}$$

$$\tilde{h}^R(t) = \tilde{h}^R(0) e^{-\xi\lambda t}. \tag{4.25}$$

From (4.6) I then solve for the evolution of good-specific consumption:

$$\begin{aligned} \tilde{c}_{ia}(t) &= \left[1 + \tfrac{n}{1-n}\delta^{R*}c^{R*}\right]^{-1} \tilde{c}^R(t) \\ \tilde{c}_{ib}(t) &= -\tfrac{n}{1-n}\delta^{R*}c^{R*}\left[1 + \tfrac{n}{1-n}\delta^{R*}c^{R*}\right]^{-1} \tilde{c}^R(t) \end{aligned} \tag{4.26}$$

The variable $\tilde{h}^R(0)$ represents the initial deviation of relative habits from the steady state. Whenever this ratio of good a to b habits lies above the steady-state ratio, $\tilde{h}^R(0) > 0$, while $\tilde{h}^R(0) < 0$ if the opposite applies. Then for a given value of $\tilde{h}^R(0)$, the paths of consumption and prices are fully determined by the familiar parameters θ, η and ξ, and λ, the convergence factor. This convergence factor can be interpreted in two ways. First, λ, multiplied by the habit adjustment speed ξ, is the rate at which habits converge to the new steady state. The greater λ, the more rapid convergence. Second, λ defines the choice of consumption c_i for a given level of our state variable, the (relative) habit. The larger the convergence factor λ, the closer good i consumption will be to its steady state for a given steady state deviation of habits. Of course, the two interpretations are related. Current consumption affects future habits, which in turn adjust more rapidly the further is consumption from the habit. Hence, one should expect convergence to be fast if c^R is close to the steady state for a given h^R. Both the former, fast convergence, and the latter, $\tilde{c}^R$ close to zero, are indeed found if λ is high. In the next two sections, I solve for the convergence factor under perfect and monopolistic competition respectively, as well as in the optimal transition path.[13]

4.5 Transition without intervention

A shift in the consumption allocation may be triggered for a number of reasons. Related to the examples discussed in the introduction, one could think of a permanent change in prices for energy or water. The introduction of an economy-wide carbon tax will likely increase energy prices. A similar price increase may be caused by the

[13] The chapter focuses on gradual transitions in response to a shock to production costs. Expression (4.23) can however also be interpreted in the context of a consumption or production quota. If the quota is binding, consumption immediately jumps to the steady state: $\tilde{c}^R(t) = 0$ for all t. This gives $\lambda = \lambda^{qt} = 1$.

shutdown of coal or nuclear power plants, or import restrictions on oil or gas, implemented for geopolitical reasons. Also global developments unrelated to a particular country's policies, such as increased energy demand from developing countries, or the depletion of oil and gas reserves will likely confront consumers with higher prices for energy. Similarly, water prices increases may be due to deliberate policy to conserve water reserves, or due to increased cost of obtaining and purifying (ground)water as water sources are running dry. Either of those would likely be the result of a period of prolonged drought, as we have experienced in California and Australia over the past years. With good-specific habit formation, changes in our consumption bundle in response to these price changes will be slow

In the remainder of this chapter, I evaluate the transition paths of consumption, prices and habits following a shift in relative production cost. More specifically, I assume that a sudden and permanent increase in the unit production cost of some good a relative to good b, δ_{ia}/δ_{ib}, triggers a transition of consumption from good a to good b. In line with the examples above, good a may represent energy, or water, and good b the relevant non-energy or non-water goods. To determine the transition path, I use the general solution for the out-of-steady-state behavior of consumption, prices and habits as presented in the previous section. In this solution, only the convergence factor λ was left undetermined. In this section, I solve for this convergence factor under perfect and monopolistic competition. To maximize profits, monopolistically competitive firms choose a time-varying markup on marginal cost. From (4.10), this markup is dependent not only on the elasticity of substitution across goods, but also on good-specific consumption, habits and future price changes. As a consequence, prices set by monopolistic and perfectly competitive firms diverge, and so will consumption choices under these alternative market structures. For now, I assume taxes are constant and exogenous, i.e. any type of shift in consumption does not trigger any (additional) policy intervention. Section 4.6 will assess the optimal transition path, and the paths of good-specific taxes and subsidies required to implement it. In any case, as relative consumption c^R will be lower in the new steady state, initial relative habits are too high: $\tilde{h}^R(0) > 0$.[14]

[14]Note that if all goods i would be hit by the same proportional cost shock, steady-state consumption of c_i still changes and habits need time to adjust. Steady-state *relative* consumption and habits are however unaffected (see (4.15) and (4.16)). Hence we have $\tilde{h}^R(0) = 0$ and consumption will immediately jump to the new steady-state.

4.5.1 Perfect competition

Under perfect competition, prices adjust one-for-one with marginal costs, which gives

$$\tilde{p}^R = \tilde{\tau}^R, \tag{4.27}$$

where I used that under a one-off shock $\tilde{\delta}^R = \dot{\tilde{\delta}}^R = 0$. With constant taxes I also know $\tilde{\tau}^R = \dot{\tilde{\tau}}^R = 0$. This implies $\tilde{p}^R = 0$ at all times. From (4.24) I can thus determine the value for the convergence term λ^{pc}:

Lemma 4.1. $\lambda^{pc} = 1 - \theta$

Then, from (4.23) and (4.25), I can conclude the following regarding the path of (relative) consumption and habits. The increase in relative marginal cost for good *a* causes good *a* consumption to fall relative to good *b*. In response to the drop in c^R, the relative habit falls. This induces a further decrease in relative consumption until the economy has converged to its new steady state. The transition to the steady state will be faster the faster is habit adjustment, i.e. higher is ξ. Also, a low habit persistence (low θ) implies that both the initial drop in consumption is larger, and the economy transitions more rapidly to the new steady state.

4.5.2 Monopolistic competition

Under monopolistic competition, the current price is a complex function of future consumption, price and habits. Linearizing the monopolist pricing rule as expressed by (4.10) and (4.12), around the post-tax steady state, I find

$$\begin{aligned}\tilde{p}^R = \tilde{\tau}^R - \frac{\xi\theta}{\rho\left(\eta-1\right)+\xi\left(\eta-1+\theta\right)}\left[\tilde{c}^R - \tilde{h}^R\right] \\ + \frac{\eta-1}{\rho\left(\eta-1\right)+\xi\left(\eta-1+\theta\right)}\dot{\tilde{p}}^R - \frac{1}{\rho+\xi}\dot{\tilde{\tau}}^R. \end{aligned} \tag{4.28}$$

Again, I know $\tilde{\tau}^R = \dot{\tilde{\tau}}^R = 0$. The following can then be established regarding λ^{mc}:

Lemma 4.2. $\lambda^{mc} \in \left(\lambda^{pc}, 1 + \theta\left(\eta - 1\right)^{-1}\right)$

Proof. See Appendix 4.B.1 □

Convergence is faster under monopolistic competition than under perfect competition. This is due to the fact that it is optimal for producers to increase relative prices in *excess* of the marginal cost increase. When the marginal cost shock hits, the producer of a *a*-good realizes that future demand for *a* falls below the current habit. This reduces the return to investing in the habit. In response, the producer increases the markup, and thus increase prices by more than the increase in unit production costs. For a good-b producer, the exact opposite story holds: it anticipates an increase in (relative) demand, which increases the return to the habit. A good-b producer thus chooses a lower markup than its good-a competitor. As consumption converges to the new steady state, the relative price will fall toward the long run relative price, reflecting the ratio of marginal costs.

As initially, relative prices increase by more than the increase in relative marginal costs, the drop in relative consumption under monopolistic competition is greater than the one under perfect competition. In fact, the shift in prices may be so large that c^R undershoots the long run equilibrium. One can show this is the case if $\eta - 1 < (1-\theta)\,\xi / (\rho + \xi)$. This condition is more likely satisfied if goods are weak substitutes (η is low), habits are weak yet change rapidly (low θ and high ξ) and time preference is weak (low ρ). The intuition is subtle, and relates to the sensitivity of prices to good-specific habits, compared to the sensitivity of consumption to these habits, taking prices as given. Suppose that habits are above the steady state. Then from (4.11), this causes a large drop in the shadow value of the habit, κ_{h_i} if habits affect future demand rapidly (high ξ), future returns are discounted little (low ρ), the elasticity of demand, η, is low and demand is sensitive to the habit (high θ). This drop in κ_{h_i} increases the monopolist's price p_i, which reduces c_i. The high θ however also implies consumption responds strongly to the above steady-state habit. This outweighs the effect of θ through prices; with a high θ, c^R is less likely to undershoot the long run equilibrium if $\tilde{h}^R(0) > 0$.[15]

4.6 Welfare optimization

The change in relative prices always induces the consumers to reconsider its consumption choices and, over time, shift to a new consumption bundle with fewer a goods. The consumer however is not perfectly rational. She is subject to projection bias and thereby does not anticipate future shifts in preferences through habit formation. Her consumption choices are thus likely suboptimal; the consumer may alter her consumption choices too slowly, or too rapidly. Policy can then be used to guide the consumer towards optimal choices. More specifically, a tax on good a will

[15] Lemma 4.2 can be considered a generalization of a result presented in Ravn et al. (2010). This result states that monopolistic producers may increase markups following a temporary positive marginal cost shock. An increase is more likely the more persistent the shock, and for the limiting case where the shock is fully persistent, producers always increase markups. Ravn et al. (2010) arrive at this result in a discrete-time framework where $h_{it} = c_{it-1}$. Lemma 4.2 generalizes this result to a continuous time setup with slow habit adjustment and a permanent shock. Here, I arrive at the novel result that consumption may undershoot its long run equilibrium.

encourage a more rapid reduction in good a consumption, while a subsidy will slow down the shift away from this good.[16,17]

In this section, I determine the optimal paths of consumption, prices and habits and the path of good a taxes or subsidies required to implement it. This optimal path is defined as the path that maximizes the present value of instantaneous utilities (4.1), subject to (4.2)-(4.4), taking into account the endogenous formation of habits (4.5), and the constraint on output (4.6). I thus assume the policymaker has full information regarding preferences and their evolution over time. As established in the previous section, the transition path without intervention depends on the underlying market structure. In line with this result, the paths of taxes or subsidies to implement optimal consumption choices under perfect and monopolistic competition will be different.

The policymaker maximize

$$W(t) = \int_t^\infty e^{-\rho(\nu - t)} U(\nu) d\nu \tag{4.29}$$

subject to (4.1)-(4.6). I then solve the Hamiltonian and use consumer demand (4.7) to arrive at the following rule for optimal prices:[18]

$$p_i(t) = \delta_i(t)\mu_L(t) - \xi \mu_{h_i}(t), \tag{4.30}$$

with

$$\mu_{h_i}(t) = \int_t^\infty e^{-(\rho+\xi)(\nu - t)} \frac{c_i(\nu)}{h_i(\nu)} p_i(\nu) Z(\nu) d\nu, \tag{4.31}$$

where μ_L is the shadow value of labor, μ_{h_i} the shadow value of the habit from the perspective of the policymaker, and

$$Z(\nu) \equiv \left[\frac{\theta}{\eta - 1} - \left[\gamma + \frac{\theta}{\eta - 1} \right] \left(\frac{h_i(\nu)}{H(\nu)} \right)^{\frac{\eta-1}{\eta}} \left(\frac{c_i(\nu)}{C(\nu)} \right)^{-\frac{\eta-1}{\eta}} \right]. \tag{4.32}$$

The optimal price for c_i then equals its marginal production cost, minus the marginal value of c_i due to habit formation. This value is equal to the direct effect of an

[16] Equivalently, a subsidy on good b will speed up the shift from good a to good b consumption while a tax on good b will have the reverse effect. For ease of exposition, I focus on good a taxes and subsidies. All results can easily be reinterpreted in the context of taxes and subsidies on the b-good.

[17] I focus on the use of taxes and subsidies to implement the first-best allocation. As the model features no uncertainty, any allocation implemented by a given path of taxes/subsidies can also be implemented by (time-varying) quota. Referring to Dalton and Ghosal (2011), this implies I take an (in)direct paternalistic approach to policy intervention. I thus do not consider a soft-libertarian approach, where policy would take the form of teaching the consumer to internalize the endogenous habit formation process herself.

[18] See Appendix 4.A for detailed derivations.

increase in c_i on the future habit, ξ, multiplied by the shadow value of the habit, μ_{h_i}. The shadow value of the habit captures the effect of an increase in h_i on future welfare and can be separated into two components. First, an increase in the good-specific habit increases the consumption weight w_i, which increases the benefit from c_i. Simultaneously however, through H, an increase in h_i reduces the weight of all other goods through H. The net effect is positive only if c_i/C is large relative to h_i/H. Then, an increase in the consumption weight of good i positively affects aggregate consumption C. Put differently, an increase in h_i has positive value if it brings the 'pattern' of habits (h_i/H) more in line with consumption (c_i/C).

The second component is always negative and captures the negative welfare effect of the aggregate habit benchmark. Any increase in the good-specific habit h_i increases the aggregate habit H. This rise in the consumption benchmark in turn reduces utility for a given level of effective consumption C.

4.6.1 Steady state

In steady state, consumption equals habits, both at the good-specific and the aggregate level. This in turn implies prices are constant over time. Then, from (4.31), the steady-state shadow value of the habit is

$$\mu_{h_i}^* = -\gamma \frac{1}{\rho + \xi} p_i^*, \tag{4.33}$$

which with (4.30) gives me the following solution for the optimal steady state good i price:

$$p_i^* = \delta_i \mu_L^* \left[\frac{\rho + \xi}{\rho + \xi (1 - \gamma)} \right]. \tag{4.34}$$

In steady state, whenever $\gamma > 0$, the shadow value of the habit is negative. Whereas good-specific persistence is not associated with any welfare effects in the long run, the aggregate habit causes a negative long run effect on utility which the consumer does not internalize. The larger is γ, the greater is this negative externality on the future self (i.e. negative internality), which translates into a higher steady-state markup. More rapid adjustment of consumption to the habit, combined with a low time preference implies the externality occurs sooner and its effect on future utility larger in present value terms. This increases the present value of the internality and thereby the optimal steady-state markup.

I can then establish the following:

Proposition 4.1. *In steady state, uniform taxes are optimal.*

Proof. By (4.34), the optimal relative price in steady state equals $p^{R*} = \delta^{R*}$. Then by (4.16), the optimal relative tax must satisfy $\tau^{R*} = 1$. □

As habits and market power affect demand and supply of all goods to an equal extent, the steady-state allocation of consumption across goods is not distorted by habits or market power. Hence, habits do not provide a rationale for taxing or subsidizing one good more aggressively than another in the long run. As pointed out before, without saving and with inelastic labor supply, consumption decisions are fully determined by relative prices. As a consequence, any uniform tax, including zero taxes, is optimal.[19]

As will be demonstrated in the next section, this result only holds in the steady state. Along the transition towards the steady state, taxes and subsidies may be required to implement optimal consumption choices.

4.6.2 Transition and policy

To determine the optimal path of consumption, prices and habits as consumption transitions away from good a to good b I adopt the same approach as in Section 4.5, where I solved for the convergence factor λ under perfect competition and monopolistic competition. With (4.23) and (4.24), this convergence factor pins down the paths of consumption and prices outside the steady state. To find the λ for the optimal path, λ^{opt}, I first linearize (4.30) and (4.31) to find

$$\tilde{p}^R = -\frac{1}{\eta}\frac{\xi\,(\theta-\gamma)}{\rho+\xi\,(1-\gamma)}\left[\tilde{c}^R-\tilde{h}^R\right]+\frac{1}{\rho+\xi\,(1-\gamma)}\dot{\tilde{p}}^R. \tag{4.35}$$

I can then establish the following regarding λ^{opt}:

Lemma 4.3. $\lambda^{opt} \in (\min\{1-\gamma,\, \lambda^{pc}\}, \max\{1-\gamma,\, \lambda^{pc}\})$ *and* $\lambda^{opt} < \lambda^{mc}$.

Proof. See Appendix 4.B.2 □

From which follows

[19] If we would extend the model with endogenous labor supply such as in Cremer et al. (2010), or allow for saving, as in Abel (1990) or Carroll et al. (2000), price and tax level changes would affect consumption levels. Now, due to noninternalized habits, the steady-state consumption level is likely inefficient. In such a case, from (4.12), (4.14) and (4.34), a steady-state habit tax equal to $T^* = \frac{\rho+\xi}{\rho+\xi(1-\gamma)}$ and $T^* = \frac{1}{\eta}\frac{(\rho+\xi)(\eta-1)+\xi\theta}{\rho+\xi(1-\gamma)}$ under perfect and monopolistic competition respectively implements the first-best steady-state consumption (note I implicitly assume the equilibrium wage is now equal to μ_L). Such an extension would also generate an observable effect of aggregate habits on consumption, and therefore allow us to infer the appropriate γ. Note that results concerning consumption, price and tax *ratios* are independent of the *levels* of these variables, and thus independent of assumptions regarding labor supply and savings.

Proposition 4.2. *Suppose goods are produced under perfect competition. If $\gamma > (<)\theta$, it is optimal to slow down (speed up) the transition by introducing a positive transitory subsidy (tax) on good a. If $\gamma = \theta$ zero subsidies (taxes) are optimal.*

Proof. Under perfect competition, by (4.27), $\tilde{\tau}^R(t) = \tilde{p}^R(t)$. $\tilde{p}^R(t)$ in turn is characterized by (4.24) where in the optimum $\lambda = \lambda^{opt}$ and I know $\tilde{h}^R(0) > 0$. This gives $\tilde{\tau}^R(t) > 0$ and falling over time whenever $\lambda^{opt} > \lambda^{pc}$. By Lemma's 4.1 and 4.3 this is the case whenever $\gamma < \theta$. Similarly, $\tilde{\tau}^R(t) < 0$ and rising over time if $\gamma > \theta$ while $\tilde{\tau}^R(t) = 0$ for all t if $\gamma = \theta$. □

If we take the transition where consumers face a flat price schedule with $p^R = p^{R*}$ as a benchmark, it is optimal to speed up the transition from good a to b if the good-specific habit parameter θ is larger than the aggregate habit parameter γ, whereas the opposite holds if $\gamma > \theta$. This result can be explained as follows. The consumer does not internalize the effect of current consumption on future habits. These habits however do affect future utility through the consumption weights w_i and the aggregate habit H. Whether a slower or faster shift in consumption from a to b is welfare-improving then depends on whether a slower or faster shift in habits increases future utility through w_i and H.

Starting with the effect through w_i, I find that a faster transition is welfare-improving. This can be seen as follows. The increase in p^R induces the consumer to shift consumption away from good a and towards good b. This shift causes a larger increase (smaller drop) in future effective consumption C the higher is the weight of good b relative to good a. Hence, future effective consumption C increases if the weight of good b, relative to good a, rises. This can be achieved by building habit in good b, and divesting habit in a, which is in turn requires consumption to more rapidly shift away from good a and towards good b. To summarize, building b habit is beneficial if b consumption is rising, and conversely, a relatively high a habit is costly if good a consumption is falling. Hence, the consumer benefits from more rapidly getting rid of this a habit.

Second, good-specific habits negatively affect welfare as through H, they jointly act as a benchmark against which effective consumption is evaluated. The transition offers an opportunity to manage, i.e. reduce, this benchmark H. As it turns out, this argues in favor of a slow transition away from good a consumption. Although not immediate, the result is intuitive. At each point in time, the consumer chooses a and b consumption such that it maximizes effective consumption C. Following an increase in the relative price for good a, the consumer moves away from this good, as postponing, or slowing down this shift, would give the consumer lower effective consumption C. A slow transition however also has an advantage, as 'too high' consumption of the now relatively expensive good pulls down the reference habit H.[20]

If $\theta = 0$, the consumption weights w_i are independent of habits and hence habits do not cause good-specific consumption persistence. This implies the first effect is absent, and only the second effect, arguing in favor of a slower transition, is relevant. Similarly, if $\gamma = 0$, the benchmark H does not affect utility for given C, and habits only affect future utility through w_i. More generally, which of the two mechanisms dominates depends on whether habits are stronger at the good-specific or at the aggregate level. This can be evaluated by a simple condition comparing the deep habit strength, θ, to the aggregate habit strength, γ, as described in Proposition 4.2.

To implement a slower (faster) transition, the initial relative price $p^R(0)$ should be below (above) the long run p^R. More specifically, the optimal consumption path is implemented if relative prices follow the path as described by (4.23), with $\lambda = \lambda^{opt}$. Under perfect competition, this path can be straightforwardly implemented by introducing a good a tax or subsidy such that $\tilde{\tau}^R(t) = \tilde{p}^R(t)$, with $\tilde{p}^R(t)$ again given by (4.24) and $\lambda = \lambda^{opt}$.[21]

As described in Section 4.5, strategic behavior by the monopolist increases the relative price p^R in excess of the increase in relative marginal costs. As a consequence, compared to the benchmark with $p^R = p^{R*}$, the shift in consumption from good a to b is already faster to begin with. One would thus expect that a subsidy on a, which slows down the transition, is more likely optimal in the presence of market power. I can show this indeed the case by solving for the value of $\tilde{\tau}^R\,(t)$ required to implement a given λ under monopolistic competition:

$$\tilde{\tau}^R(t) = \frac{1}{\eta}\left[\frac{(\theta-1)\left[(\rho+\xi)+\xi\frac{\theta}{\eta-1}\right]+\lambda\,(\rho+\xi\lambda)}{(\rho+\xi)+\xi\frac{\theta}{\eta-1}}\right]\frac{\rho+\xi}{\rho+\xi\,(1+\lambda)}\tilde{h}^R(t) \qquad (4.36)$$

This expression has been derived by (4.23) and (4.28) and allows me to establish the following:

Proposition 4.3. *Suppose goods are produced under monopolistic competition. Then it is optimal to slow down the transition by introducing a positive transitory subsidy on good a.*

[20] As an extreme example, think of the following. Suppose consumption consists of apples and oranges. Then a strong increase in the price of apples initiates a shift towards oranges in the consumption bundle. Suppose the consumer is stubborn, and initially sticks to an apple-intensive diet. Since apples are very expensive, the consumer can afford only a few and is very hungry. The next period, the consumer decides to spend less on apples such that he can buy many oranges. As the consumer was used to starving in the previous period (H dropped a lot), the increase in orange consumption and elimination of hunger constitutes a large welfare gain.

[21] The closed-form solution for λ^{opt} can be found in Appendix 4.B.

Proof. Under monopolistic competition, the relative tax is determined by (4.36), where I know $\tilde{h}^R(t) > 0$ for finite t. By definition, $\tilde{\tau}^R(t) = 0$ for $\lambda = \lambda^{mc}$. By Lemma 4.3, I know $\lambda^{opt} < \lambda^{mc}$. Hence, we must have $\tilde{\tau}^R(t) < 0$. As $\tilde{h}^R(t)$ converges to zero as $t \to \infty$, so will $\tilde{\tau}^R(t)$. □

The monopolist always implements a transition that is too rapid from a welfare perspective. First, the monopolist does not take into account the benefits of a slow transition in bringing down the aggregate habit H. Yet even if $\gamma = 0$, i.e. even if the benchmark habit plays no role in determining utility from consumption C, a welfare-maximizing policy slows down the shift in consumption from a to b under monopolistic competition. This is because of the following. We know that along the transition, there is a benefit to quickly 'rebalancing' the consumption weights w_i such that they become more in line with actual consumption. The monopolist recognizes this too, yet it internalizes only the effect of the habit on its own consumption weight. As demand for good a falls over time, investing in the habit has become less valuable. As a response, the monopolist increases its markup to quickly divest habit and thus reduce the consumption weight. This however, increases the consumption weight of all other goods, and therefore leads to a more rapid rebalancing of the w_i. In fact, this rebalancing is too rapid from the perspective of the policymaker. Hence, (partially) countering the monopolist's response to increase prices when habits are 'too high' increases welfare.

4.7 Application; residential water use in California

To illustrate the adjustment path of consumption and assess the quantitative implications of habit formation I consider the following stylized application of the framework to water use restrictions in California. Several years of severe drought have led to major water shortages in California. As a response to these shortages, on April 1 2015, Californian governor Brown mandated water use reductions of 25 percent in cities and towns. To achieve this cut, lawns were replaced by more drought-tolerant landscaping and the watering of grass on public street medians was banned. In addition, campaigns have been initiated to encourage Californians to reduce water use.[22] These measures were effective; in June, water use was down by 27.3 percent, and a 31.3 percent reduction was achieved by July 2015 (State of California, 2015b).

In the application below, I consider the introduction of permanent water charges that implement an equivalent 25 percent long run drop in residential water use. Wa-

[22] For instance, on saveourwater.com, Californians can find advice on how to save water. On savewater.ca.gov, they can report water waste, such as 'watering the wrong time of day' or 'serving water in an eating or drinking establishment without request'.

ter charges may be fully passed through to consumers, or producers may act strategically and adjust markups in response to the charge. In either case, due to habits in water consumption, water demand does not instantly jump to the new steady state. I simulate the paths of consumption and prices as the economy converges to its new steady state. I compare the paths under perfect and monopolistic competition to the optimal consumption path as well as the path imposed by the Californian mandate. Temporary subsidies will be required to implement the optimal consumption path. These subsidies can be interpreted as temporary discounts on the permanent water charge, or simply a slow phase-in of this charge. Finally, I compute the welfare gain of implementing an optimal path instead of the alternative adjustment paths.

To obtain numerical results I discretize the model. More details about this discretization can be found in Appendix 4.C.

4.7.1 Parameter choices

The parameter values are determined as follows. On average, a Californian pays \$40-\$70 a month for water. On a yearly basis, this corresponds to 1 to 2 percent of average per capita income (BEA, 2015; CNBC, 2015). Based on this, I set n, the share of a goods, which in the case at hand represent 'residential water', equal to 0.015. I set the initial δ_i's equal to 1 for all goods. Then, as of time $t = 0$, water will be subject to an additional charge, such that δ_i rises to some $\delta_i^+ > 1$ for $i \in [0, n]$. I set $\eta = 2$. With $\theta = 0.4$, a 25 percent reduction in steady-state water consumption requires an increase in the cost of water relative to non-water goods by 9.1 percent: $\delta_i^+ = 1.091$.[23]

The habit parameters θ and γ are major determinants of the rate at which a transition away from water consumption takes place, and the type of policy required to maximize welfare along the transition. Several approaches can be used to infer the appropriate values for these parameters.

For θ, I consider empirical research on good-specific consumption persistence, and research that estimates both the short- and long run price elasticity of demand. Under the former approach, estimates for θ range from zero to 0.72, with a central value of about 0.3 (Bronnenberg et al., 2012; Carrasco et al., 2005; Verhelst and Van den Poel, 2014; Zhen et al., 2011). With the exception of Bronnenberg et al. (2012), these estimates use (a measure of) previous month or quarter consumption expenditure as a benchmark. The appropriate benchmark is however not immediate, and

[23]In our framework, the elasticity of substitution directly determines the price elasticity of demand. Empirical estimates for the latter for specific consumer goods typically deliver low values, which are often below 1, suggesting complementarity (see for instance Baltagi et al., 2000; Espey et al., 1997; Scott, 2015; Zhen et al., 2011). Larger scale calibrations require values above 4 to match observed markups (Ravn et al 2006; 2010). I take a middle ground here and set $\eta = 2$. The choice of θ will be motivated below.

if habits are persistent, these estimates may either under- or over-estimate the 'real' θ. Bronnenberg et al. (2012) instead use geographic variation in brand preferences to elicit the causal effect of past experiences on future preferences. They find that 60 percent of the gap in brand preferences can be attributed to supply-side factors, while endogenous and persistent brand preferences explain 40 percent of the geographic variation in brand market shares. This corresponds to $\theta = 0.4$.[24]

An alternative estimation procedure for θ does not face the 'benchmarking' problem either. This approach is based on short- and long-run price elasticities of demand. From Section 4.4.1, I know these are equal to $\varepsilon_C^{SR} = \eta$ and $\varepsilon_C^{LR} = \eta/(1-\theta)$ respectively. Then $\theta = 1 - \varepsilon_C^{SR}/\varepsilon_C^{LR}$. Espey et al. (1997) conduct a meta analysis of price elasticities for residential water consumption. Based on their median estimates for short and long run elasticities, I find a θ equal to 0.41. Scott (2015) presents an overview of estimates of the elasticity of gasoline demand. The central value for θ based on these estimates is 0.6. Baltagi et al. (2000) estimate cigarette demand and also arrive at a value of 0.6.[25] Demand persistence for gasoline and cigarettes however likely overestimates the persistence of a 'representative' good: cigarettes are highly addictive and short run gasoline demand is to a large extent determined by the vehicle a consumer owns. For this reason, I consider the estimate of 0.6 to be an upper bound for the appropriate θ and in the remainder, I set $\theta = 0.4$.

For γ, I consider estimates based on empirical evidence related to the Easterlin paradox and hedonic adaptation, aggregate consumption persistence and calibrations. High values for γ (close to 1) are also required to explain the Easterlin paradox (Easterlin, 1974; Easterlin et al., 2010). Although evidence for happiness, or hedonic, adaptation is robust, the strong form of the Easterlin paradox, where long-run happiness is unaffected income changes, is heavily contested (Clark, 1999; Easterlin et al., 2010; Oswald and Powdthavee, 2008; Stevenson and Wolfers, 2008). With incomplete adaptation, the value of γ is not easily determined, as reported happiness scores cannot be directly translated to our utility measure.

In my framework, to focus on consumption shifts across sectors, I abstract from saving and capital accumulation. If intertemporal consumption tradeoffs are take into account, the aggregate habit parameter γ plays an additional role in determin-

[24]In the model, p^R captures the supply-side factors. Let $\ln\left(c_x^R/c_y^R\right) = \ln\left(h_x^R/h_y^R\right)$ capture the steady-state difference in demand and habits between in regions x and y. Now suppose a consumer j moves from region x to y, such that supply-side factors are now equal and relative consumption of this consumer now equals $c_{j,x\to y}^R$. Keeping habits constant, from (4.7), $c_{j,x\to y}^R/c_1^R = \left(h_x^R/h_y^R\right)^\theta$, or $\ln\left(c_{x\to y}^R/c_y^R\right) = \theta\ln\left(h_x^R/h_y^R\right) = \theta\ln\left(c_x^R/c_y^R\right)$.

[25]Baltagi et al. (2000) compare a large number of models. I use the estimate of the model they consider best-performing.

ing the degree of aggregate consumption persistence.[26] Empirically estimating this persistence, Ravina (2005) and Alvarez-Cuadrado et al. (2012) find that a 1 percent increase in past aggregate consumption increases current consumption by 0.3 to 0.5 percent. The corresponding estimate for γ then depends on the σ chosen. For $\sigma = 2$, γ lies in between 0.6 and 1, and higher γ are found for lower σ.[27]

Finally, I turn to calibrations. In a model that allows for saving, Abel (1990) requires values for γ close to 1 to explain the equity premium puzzle. Fuhrer (2000) introduces habits in a monetary policy model and estimates γ to fit the data. He arrives at a value of 0.8 to 0.9. Overall, evidence seems to suggest higher values for γ than θ. I follow Fuhrer (2000), and set $\gamma = 0.8$.[28]

Fewer empirical guidance exists regarding the speed of habit adjustment, ξ. Ravn et al. (2012) and Bronnenberg et al. (2012) find habits to adjust very slowly over time; on an annual basis ξ is equal to 0.05 and 0.025 respectively. This slow adjustment is in line with Logan and Rhode (2010) and Atkin (2013), who find that prices (more than) 10 years in the past can partly explain current patterns of food consumption. Carroll et al. (2000) adopt an annual value of 0.2 while Constantinides (1990) requires values as high as 0.6 to explain the equity premium puzzle. Finally, much of the literature takes habits as equal to past-year consumption. I take a 50 percent annual adjustment. As I estimate the model on a monthly basis ($dt = 1$ month), this gives $\xi = 0.056$. Finally, I set the monthly discount rate ρ equal to $\rho = 0.0035$,[29] the elasticity of marginal utility to $\sigma = 1.5$ and total labor supply $L = 1$. With initial marginal production cost δ_i equal to 1 for all i, this gives initial steady state consumption, habits and prices equal to 1 for all goods. An overview of all parameter values can be found in Table 4.1.

4.7.2 Results

Figure 4.1 shows the response of residential water consumption and prices relative to the a 'non-water' consumption bundle following the introduction of the permanent water charge of 9.1 percent at at time 0. The dashed and dotted curves depict the response under perfect and monopolistic competition respectively, without any

[26]See for instance Carroll et al. (2000), Fuhrer (2000), Alvarez-Cuadrado et al. (2004) and Diaz et al. (2003). See also footnote 19.

[27]For $\sigma = 1$, aggregate consumption demand is independent of the habit. For $\sigma < 1$, $\gamma < 0$ is required to generate aggregate persistence.

[28]Dynan (2000) and Guariglia and Rossi (2002) estimate consumption persistence based on aggregate food consumption. As food is still a broad aggregate, I cannot readily reinterpret their estimates as estimates of θ or γ. They both find no or negative consumption persistence. However, their estimates, as well as those by Ravina (2005) and Alvarez-Cuadrado et al. (2012), suffer from the same 'benchmarking' problem discussed before.

[29]This corresponds to an annual discount rate of about 4 percent.

Table 4.1: Parameter values

Parameter	Value	Description
σ	1.5	Elasticity of marginal utility
ρ	0.0035	Rate of time preference (monthly)
η	2	Elasticity of substitution
θ	0.4	Deep habit strength
γ	0.8	Aggregate habit strength
ξ	0.056	Habit adjustment speed (monthly)
n	0.015	Share of type a (water) goods
δ_{ia}	$\{1, 1.091\}$	Water unit production cost, excluding and including the water charge
δ_{ib}	1	Non-water unit production cost
L	1	Labor supply

additional policy intervention. The solid curves depict the optimal paths and the dash-dotted curves those under the mandate.

Under perfect competition, consumers face a one-off increase in prices (see Figure 4.1b). In response to this price increase, consumers instantly reduce water consumption by 16 percent.[30] The remaining 9 percent reduction is achieved as habits fall over time and consumption follows this drop in habit. As expected, the shift away from residential water consumption is faster under monopolistic competition: at $t = 0$ consumption immediately drops by 23 percent. Following this drop, also habits quickly adjust. The rapid consumption response is the consequence of strategic behavior; under monopolistic competition, prices for residential water relative to the non-water bundle increase by an additional 4.2 percent (46 percent of the underlying cost shift). Under the mandate, consumption immediately drops by 25 percent. This corresponds to an (implicit) price increase by more than 15 percent. As time passes, habits adjust, and the price required to ensure the mandate is met falls.

Along the transition to the new steady state, neither the consumption choices along the monopolistic competition nor perfect competition path are optimal. From Proposition 4.3 we know that the monopolist always implements a transition that is too rapid. For our parameter values we have $\gamma > \theta$. Then Proposition 4.2 informs us that also the shift away from water consumption under perfect competition is faster than optimal. This can also be seen in Figure 4.1a, where water consumption is higher along the optimal path (solid curve) than along the paths where the transition is not specifically managed (dashed and dotted curves). In the optimum, time 0 water consumption falls by only 10 percent. Consumption continues to drop af-

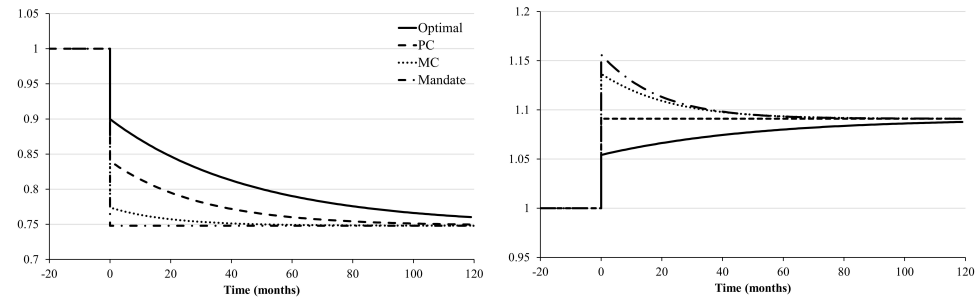
[30] Figure 4.1a depicts relative consumption paths. As the price change only affects 1.5 percent of goods, demand for all other goods increases by less than 0.3 percent at any point during the transition. The difference between changes in absolute water consumption, and consumption of water relative to non-water goods is thus minor, and I use the two concepts interchangeably.

terwards, yet it takes more than 10 years until the 25 percent water reduction goal is met. To ensure consumers select these optimal consumption levels, the relative price for water should only increase by 5.4 percent initially, and then slowly rise to its long run level of 1.091.

Figure 4.1: Transition away from water consumption

(a) Water relative to non-water consumption

(b) Water relative to non-water price



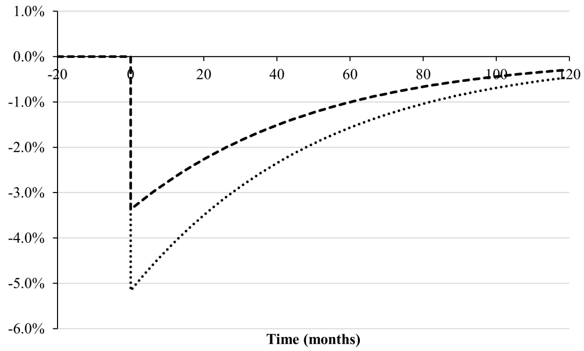
The dashed (dotted) curve the path under perfect (monopolistic) competition when firms are confronted with a permanent water charge, introduced at $t = 0$. The dash-dotted curve depicts the mandate as implemented by the Californian government. Solid curves depict the optimal path. I assume the economy is in steady state for all $t < 0$.

For water, local authorities may be able to directly manage prices. If this is the case, directly implementing a price path according to the solid line in Figure 4.1b is optimal. This implies that until the economy is in steady state, consumers receive a temporary discount, or subsidy, on the water charge. This subsidy is equivalent to the optimal subsidy if water is supplied under perfect competition. The optimal transitory subsidy, as shown by Figure 4.2, is then equal to 3.4 percent. This is more than a third of the 9.1 percent water charge. Such a transitory subsidy must be larger if the good is supplied by monopolistic firms, who initially increase prices in excess of the charge. Now, an initial subsidy of 5.2 percent, which falls to 4.1 percent after 1 year and 1.6 percent after 5 years is optimal.

The subsidies have a large impact on prices and consumption choices as the economy reduces its water consumption. This raises the question of whether this policy generates sizeable welfare gains. For this purpose, I compute the consumption-equivalent welfare loss due to the transition. This loss is computed for the paths presented in Figure 4.1a. Note that for the mandate, even though consumption immediately jumps to its long run level, habits still require time to adjust. Next, I define the welfare gain of intervention as the losses forgone by implementing the optimal consumption path as a share of the loss under this optimal path.[31] The results are

[31]More formally, let W_X be welfare under consumption path X and W^* (C^*) welfare if the economy

Figure 4.2: Water relative to non-water optimal transitory tax rate



The dashed (dotted) curve depict the optimal relative tax path under perfect (monopolistic) competition when firms are confronted with a permanent water charge, introduced at $t = 0$. I assume the economy is in steady state for all $t < 0$.

presented in Table 4.2.

From Figure 4.1a I know that water reductions are relatively slow along the optimal path, and fast under monopolistic competition. A mandate which immediately implements steady-state consumption levels implies an even faster transition. Hence, I expect the potential gains from intervention to be largest under monopolistic competition and the mandate. This is confirmed by Table 4.2. Ensuring consumers face an appropriate upward-sloping price schedule as opposed to the flat schedule under perfect competition, or falling schedule under monopolistic competition, reduces welfare losses by 1.3 and 4.5 percent respectively. The mandate, which does not take into account that consumers have habits and prefer a slow adjustment in water consumption, increases welfare losses along the transition by 6 percent.

Table 4.2: Potential welfare gain of intervention

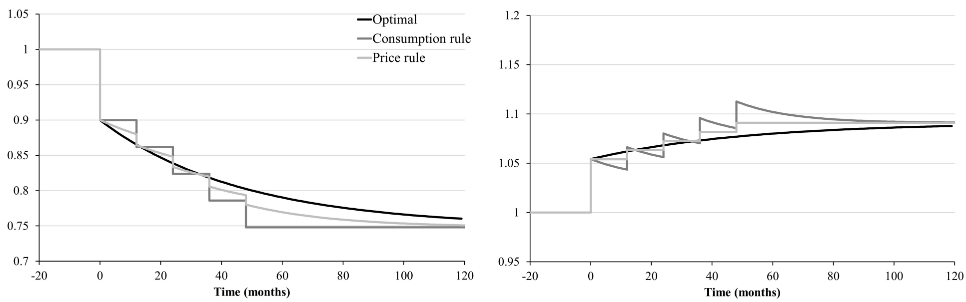
Benchmark	Gain
Perfect competition	1.32%
Monopolistic competition	4.52%
Mandate	5.97%

is in steady-state. Then the (steady-state) consumption-equivalent welfare loss is β_X, with β_X implicitly determined by $W_X = W^*\left((1-\beta_X)\,C^*\right)$. The welfare gain of intervention is then $\left(\beta_X - \beta_{opt}\right)/\beta_{opt}$ where the subscript opt indicates the optimal path.

Rule of thumb policy Even though the optimal path minimizes welfare losses, the other three paths have a clear advantage in terms of the amount of information and planning required to implement them. Under the perfect and monopolistic competition path, policy takes the form of a one-off increase in the water charge, without any further intervention. The mandate instead, implements a one-off drop in water consumption. Of these three paths, the perfect competition path, where consumers face a flat price schedule, performs best. In this paragraph, I propose two 'rule of thumb' policies which reduces welfare losses compared to this perfect competition path, yet are more straightforward to implement than the optimal path. The first rule of thumb policy is a water quota, that is lowered each year. In the first year, it imposes a 10 percent water reduction. Then each year, for four consecutive years, the quota is lowered by 3.75 percentage points, until after 4 years, the total 25 percent water reduction is achieved.[32] This rule targets consumption, and can thus be compared to the mandate. The second rule of thumb policy targets water prices. It sets a relative price of water equal to 1.054 in the first year, and increases this price by 0.925 percentage points each year thereafter. Figure 4.3 presents the paths of water consumption and prices under both rules of thumb, and optimal policy. As is clear from Figure 4.3a, both rules implement a shift away from water consumption that is somewhat slower than optimal initially, yet reaches the steady state sooner. Under the consumption rule, (implicit) prices overshoot the long run equilibrium for a substantial period of time.

Figure 4.3: Transition under rules of thumb

(a) Water relative to non-water consumption (b) Water relative to non-water price



Curves depict policy rules where policy is introduced at $t = 0$. I assume the economy is in steady state for all $t < 0$.

[32]The 4 year period is chosen as follows. Appendix 4.B presents the closed-form solutions for λ^{opt}. For our parameter values, we have $\lambda^{opt} = 0.3668$. Then the adjustment speed, $\xi \cdot \lambda$, is about 2 percent a month. A rough approximation of the total adjustment period is then $1/0.02 = 50$ months$\approx$4 years. I take the 10 percent initial drop in water consumption of the optimal path, after which 15 percentage points remain. Then the annual reduction is set equal to $15/4 = 3.75$ percentage points. The approach to determine the rule of thumb price path is equivalent.

The simple policy rules clearly improve upon the allocation with the flat price schedule. Under the consumption rule, the welfare loss of the transition is 0.83% greater than the equivalent loss with optimal intervention. The price rule performs even better, here I find this percentage reduced to 0.19%.

Accuracy of the linear approximation As a final exercise, I compare the calibration results to the linear approximation of the consumption path in (4.23). I find that this approximation is accurate. For the parameter values in Table 4.1 we have $\lambda^{pc} = 0.6$, $\lambda^{mc} = 0.91$ and $\lambda^{opt} = 0.37$ and $\tilde{h}^R(0) = 1/3$.[33] Then, from (4.23), time 0 water relative to non-water consumption equals $c^R(0) = \{0.85, 0.77, 0.91\}$ under perfect competition, monopolistic competition and the optimal path respectively. Comparing these values to the results discussed above I find that the approximation is off by at most 1 percentage point. The linear approximation is accurate too regarding the adjustment speed. For the reduction in water consumption that remains after the initial drop, the approximation predicts a half life of 21, 14 and 34 months for perfect competition, monopolistic competition and the optimal path respectively.[34] This approximation is slightly off only for the half life under the optimal path; here the calibration puts the half life at 33 months.

4.8 Conclusion

In the upcoming decades, some major shifts will likely occur in our consumption patterns. Increased water shortages in many regions in the world necessitate consumers to reduce water use. Resource scarcity and concerns about climate change will call for a reduction in energy use, especially if the cost of renewable energy remains high. Such changes within our consumption bundles will not happen from one day to another. One of the reasons is that people are subject to habit formation, which causes persistence in consumption. Habits may also affect welfare, by acting as a reference point against which consumption is evaluated. This raises the question whether, from a social welfare perspective, changes in consumption are too slow, or perhaps still too fast. In this chapter I answer this question. I find that if the persistence effect of habits is particularly strong, then the consumer, who does not internalize the fact that current consumption affects future habits, does not adjust its consumption bundle rapidly enough. In the welfare effect of the aggregate reference habit is strong, the opposite holds: now a slow adjustment is preferred.

[33] Also the closed-form solutions for λ^{mc} can be found in Appendix 4.B.

[34] The half life T for the approximation can be computed by solving $e^{-\xi\lambda T} = 0.5$.

The set of taxes and subsidies that implement the optimal transition path of consumption then depends on market structure. Under monopolistic competition, strategic pricing speeds up the shift within the consumption bundle to begin with. Now, a subsidy which slows down the transition is always optimal.

The application of the model to water use restrictions in California reveals effects are also quantitatively meaningful. The immediate 25 percent drop in residential water use as imposed by the Californian government increases the welfare cost of achieving long run water savings by 6 percent. The optimal path calls for a lower immediate reductions in water use, and allows the remaining water savings to slowly materialize over time. To implement this path, the policymaker offers consumers an initial discount of as much as 60 percent of the increase in water charges required to attain the 25 percent long run reduction goal. The optimal path requires careful management of water consumption and prices. I propose two rule of thumb policies that are easier to implement and still achieve sizeable welfare gains compared to the Californian mandate.

In addition to water use reductions, the framework can be used to evaluate many other shifts in consumption. As mentioned above, it could be applied to determine the optimal transition of consumption towards a less energy-intensive bundle. It could also be informative on the welfare implications of a gradual, or aggressive, introduction of 'fat taxes' or excise taxes on cigarettes. Here again the question is whether it is optimal to force consumers to very quickly get rid of these bad habits by introducing hefty initial rates. Or maybe it is optimal to allow consumers to slowly adjust their demand by implementing a tax that starts low and increases over time. In the above examples the shift in the consumption bundle is policy-induced to begin with. The same insight applies however if the cause of the shift is external. Consider for example the common call for policy action when gasoline prices increase due to shifts on world oil markets. Also shifts in food prices, caused by misharvests or increased openness to trade,[35] are often followed by appeals for government intervention such as (temporary) subsidies or tax breaks. My framework and numerical results provide support for such measures; with habit formation and projection bias, a policy that allows people to partly postpone adjustment in consumption is welfare-improving.

[35] This example relates to the work by Atkin (2013), who documents that habits reduce the nutritional gains from trade in India, as consumers continue to favor foods that were relatively inexpensive in the past.

Appendix 4

4.A Detailed derivations

4.A.1 Expressions (4.10), (4.11) and (4.28)

Under monopolistic competition, the monopolist maximizes $\Pi_i(t) = \int_t^\infty e^{-\rho(\nu-t)} c_i(\nu) \left[p_i(\nu) - \delta_i(\nu)\tau_i(\nu)\right] d\nu$, by choosing the path of supply c_i, while taking into account demand (4.7) and the process of good-specific habit formation (4.5). The producer does however not internalize the effect of its supply decisions on P or H. Hence it solves the following Hamiltonian:

$$\mathcal{H} = c_i \left[p_i - \delta_i \tau_i\right] + \kappa_{p_i} \left[P c_i^{-\frac{1}{\eta}} \left(\frac{h_i}{H}\right)^{\frac{\theta}{\eta}} \left(\frac{L}{P}\right)^{\frac{1}{\eta}} - p_i\right] + \kappa_{h_i} \left[\xi \left(c_i - h_i\right)\right],$$

where κ_{p_i} is the shadow value of inverse demand p_i and κ_{h_i} is the shadow value of habits h_i. This gives the following FOCs:

$$\begin{array}{ll} [c_i] & p_i - \delta_i \tau_i - \kappa_{p_i} \left[\frac{1}{\eta} \frac{p_i}{c_i}\right] + \xi \kappa_{h_i} = 0 \\ [p_i] & c_i - \kappa_{p_i} = 0 \\ [h_i] & \frac{\theta}{\eta} \kappa_{p_i} \frac{p_i}{h_i} - \xi \kappa_{h_i} = \rho \kappa_{h_i} - \dot{\kappa}_{h_i}. \end{array}$$

Then I substitute $\kappa_{p_i} = c_i$ (see FOC with respect to p_i) in the FOCs for c_i and h_i. This gives (4.10) and (4.11). Next, I take the time derivative of (4.10):

$$\dot{\kappa}_{h_i} = -\frac{1}{\xi} \left[\frac{\eta - 1}{\eta} \dot{p}_i - \delta_i \tau_i \left[\frac{\dot{\delta}_i}{\delta_i} + \frac{\dot{\tau}_i}{\tau_i}\right]\right],$$

which with the FOCs for h_i gives

$$\kappa_{h_i} = \frac{1}{\rho + \xi} \left[p_i \frac{\eta - 1}{\eta} \left[\frac{\theta}{\eta - 1} \frac{c_i}{h_i} - \frac{1}{\xi} \frac{\dot{p}_i}{p_i}\right] + \delta_i \tau_i \frac{1}{\xi} \left[\frac{\dot{\delta}_i}{\delta_i} + \frac{\dot{\tau}_i}{\tau_i}\right]\right].$$

I then substitute this result in (4.10) to find the following solution for p_i:

$$p_i = \delta_i \tau_i \frac{\eta}{\eta - 1} \left[\frac{1 - \frac{1}{\rho + \xi} \left[\frac{\dot{\delta}_i}{\delta_i} + \frac{\dot{\tau}_i}{\tau_i}\right]}{1 + \frac{1}{\eta - 1} \frac{\xi}{\rho + \xi} \theta \frac{c_i}{h_i} - \frac{1}{\rho + \xi} \frac{\dot{p}_i}{p_i}}\right].$$

This equation is in turn used to find the steady-state price (4.14), and loglinearized to arrive at (4.28).

4.A.2 Expressions (4.30), (4.31) and (4.35)

The policymaker maximizes $W(t) = \int_t^\infty e^{-\rho(\nu-t)}U(\nu)d\nu$ subject to (4.1)-(4.6). The Hamiltonian thus reads

$$\mathcal{H} = \frac{\left(CH^{-\gamma}\right)^{1-\sigma}}{1-\sigma} + \mu_C\left[\left[\int_0^1 \left(\frac{h_i}{H}\right)^{\frac{\theta}{\eta}} c_i^{\frac{\eta-1}{\eta}} di\right]^{\frac{\eta}{\eta-1}} - C\right]$$
$$+ \mu_H\left[\left[\int_0^1 h_i^{\frac{\eta-1+\theta}{\eta}} di\right]^{\frac{\eta}{\eta-1+\theta}} - H\right] + \mu_L\left[L - \int_0^1 \delta_i c_i di\right] + \mu_{h_i}\left[\xi\left(c_i - h_i\right)\right],$$

where I have slightly rewritten (4.4) and μ_C, μ_H and μ_L are the shadow values of effective consumption, aggregate habit and labor respectively, and μ_{h_i} is the shadow value of the good-specific habit. This gives the following FOCs:

$$\begin{array}{ll} [C] & \left(CH^{-\gamma}\right)^{1-\sigma}\frac{1}{C} - \mu_C = 0 \\ [H] & -\gamma\left(CH^{-\gamma}\right)^{1-\sigma}\frac{1}{H} - \mu_C\frac{\theta}{\eta-1}\frac{C}{H} - \mu_H = 0 \\ [c_i] & \mu_C C^{\frac{1}{\eta}}\left(\frac{h_i}{H}\right)^{\frac{\theta}{\eta}} c_i^{\frac{\eta-1}{\eta}}\frac{1}{c_i} - \delta_i\mu_L + \xi\mu_{h_i} = 0 \\ [h_i] & \mu_C\frac{\theta}{\eta-1}C^{\frac{1}{\eta}}\left(\frac{h_i}{H}\right)^{\frac{\theta}{\eta}} c_i^{\frac{\eta-1}{\eta}}\frac{1}{h_i} + \mu_H H^{\frac{1-\theta}{\eta}} h_i^{\frac{\eta-1+\theta}{\eta}}\frac{1}{h_i} - \xi\mu_{h_i} = \rho\mu_{h_i} - \dot{\mu}_{h_i}. \end{array}$$

First I observe that $P = dU/dC = \mu_C$ and $PC = L$. Then I can rewrite (4.7) to

$$p_i = \mu_C\left(\frac{c_i}{C}\right)^{-\frac{1}{\eta}}\left(\frac{h_i}{H}\right)^{\frac{\theta}{\eta}}, \tag{4.A.1}$$

which with the FOC for c_i gives (4.30). Then to arrive at (4.31), I first substitute $\mu_C = \left(CH^{-\gamma}\right)^{1-\sigma}\frac{1}{C}$ in the FOC for H. This gives $\mu_H = -\mu_C\frac{C}{H}\left[\gamma + \frac{\theta}{\eta-1}\right]$. I then substitute these results for μ_C and μ_H and (4.A.1) in the FOC for h_i to find

$$\mu_{h_i} = \frac{1}{\rho+\xi}\left[\dot{\mu}_{h_i} + \frac{c_i}{h_i}p_i\left[\frac{\theta}{\eta-1} - \left[\gamma + \frac{\theta}{\eta-1}\right]\left(\frac{h_i}{H}\right)^{\frac{\eta-1}{\eta}}\left(\frac{c_i}{C}\right)^{-\frac{\eta-1}{\eta}}\right]\right], \tag{4.A.2}$$

which then gives (4.31). Next, I take the time derivative of (4.30):

$$\dot{\mu}_{h_i} = -\frac{1}{\xi}\left[\dot{p}_i - \delta_i\mu_L\left[\frac{\dot{\delta}_i}{\delta_i} + \frac{\dot{\mu}_L}{\mu_L}\right]\right],$$

and substitute this in (4.A.2) which gives me:

$$\mu_{h_i} = \frac{1}{\rho+\xi}\left[p_i\left[\frac{c_i}{h_i}Z - \frac{1}{\xi}\frac{\dot{p}_i}{p_i}\right] + \delta_i\mu_L\frac{1}{\xi}\left[\frac{\dot{\delta}_i}{\delta_i} + \frac{\dot{\mu}_L}{\mu_L}\right]\right], \tag{4.A.3}$$

where, as in the main text

$$Z \equiv \left[\frac{\theta}{\eta-1} - \left[\gamma + \frac{\theta}{\eta-1}\right]\left(\frac{h_i}{H}\right)^{\frac{\eta-1}{\eta}}\left(\frac{c_i}{C}\right)^{-\frac{\eta-1}{\eta}}\right].$$

I then substitute this result in (4.10) to find the following solution for the optimal price:

$$p_i = \delta_i\mu_L\left[\frac{1-\frac{1}{\rho+\xi}\left[\frac{\dot{\delta}_i}{\delta_i}+\frac{\dot{\mu}_L}{\mu_L}\right]}{1+\frac{\xi}{\rho+\xi}\frac{c_i}{h_i}Z - \frac{1}{\rho+\xi}\frac{\dot{p}_i}{p_i}}\right],$$

which can in turn be loglinearized to find (4.35).

4.B Proofs

4.B.1 Proof to Lemma 4.2 (λ^{mc})

First I take the time derivative of the loglinearized the consumer demand function (4.20):

$$\dot{\tilde{c}}^R = -\eta\dot{\tilde{p}}^R + \theta\dot{\tilde{h}}^R. \tag{4.B.1}$$

Next, loglinearizing (4.5) allows me to write

$$\dot{\tilde{h}}^R = \xi\left[\tilde{c}^R - \tilde{h}^R\right]. \tag{4.B.2}$$

Then using (4.20), (4.B.1) and (4.B.2) in (4.28) and observing that under constant taxes and a one-off shock $\tilde{\tau}^R = \dot{\tilde{\tau}}^R = 0$ and $\tilde{\delta}^R = \dot{\tilde{\delta}}^R = 0$, I find the following expression for change in $\tilde{c}^R$ as a function of $\tilde{c}^R$ and h^R:

$$\dot{\tilde{c}}^R = (\rho+\xi)\,\tilde{c}^R - \frac{\theta}{\eta-1}\left[(\rho+\xi)(\eta-1)+\xi(\theta-1)\right]\tilde{h}^R. \tag{4.B.3}$$

This in turn gives the following system of dynamic equations:

$$\begin{bmatrix}\dot{\tilde{h}}^R\\ \dot{\tilde{c}}^R\end{bmatrix} = \begin{bmatrix}-\xi & \xi\\ -\frac{\theta}{\eta-1}\left[(\rho+\xi)(\eta-1)+\xi(\theta-1)\right] & \rho+\xi\end{bmatrix}\begin{bmatrix}\tilde{h}^R\\ \tilde{c}^R\end{bmatrix}.$$

From (4.23) and (4.25) I have $\dot{\tilde{h}}^R = -\xi\lambda\tilde{h}^R$ and $\dot{\tilde{c}}^R = -\xi\lambda\tilde{c}^R$, so

$$0 = \begin{bmatrix} -\xi\left(1-\lambda^{mc}\right) & \xi \\ -\frac{\theta}{\eta-1}\left[(\rho+\xi)(\eta-1)+\xi(\theta-1)\right] & \rho+\xi\left(1+\lambda^{mc}\right) \end{bmatrix} \begin{bmatrix} \tilde{h}^R \\ \tilde{c}^R \end{bmatrix},$$

and λ^{mc} is implicitly determined by

$$R^{mc}\left(\lambda^{mc}\right) = (\theta-1)\left[(\rho+\xi)+\xi\frac{\theta}{\eta-1}\right]+\lambda^{mc}\left[\rho+\xi\lambda^{mc}\right]=0.$$

First, as $\theta < 1$, I know $R^{mc}(0) < 0$. Then as $dR^{mc}/d\lambda^{mc} > 0$ for $\lambda^{mc} > 0$ I know there exists a solution $\lambda^{mc} > 0$. Next $R^{mc}(\lambda^{pc}) = -\lambda^{pc}\xi\theta\eta\left(\eta-1\right)^{-1} < 0$, from which I can conclude that $\lambda^{pc} < \lambda^{mc}$. Hence convergence is faster under a monopolistic competition than under perfect competition. Then for $\lambda' = 1+\theta\left(\eta-1\right)^{-1}$ we have $R^{mc}\left(\lambda'\right) = \theta\frac{\eta}{\eta-1}\left[(\rho+\xi)+\xi\frac{\theta}{\eta-1}\right] > 0$ from which I know $\lambda^{mc} < 1+\theta\left(\eta-1\right)^{-1}$.

The closed-form solution for λ^{mc} then reads:

$$\lambda^{mc} = \frac{\sqrt{\rho^2-4\xi(\theta-1)\left[(\rho+\xi)+\xi\frac{\theta}{\eta-1}\right]}-\rho}{2\xi}.$$

□

4.B.2 Proof to Lemma 4.3 (λ^{opt})

The optimal path of consumption can be found by (4.30), (4.20), (4.B.1) and (4.B.2) where I set $\tilde{\delta}^R = \dot{\tilde{\delta}}^R = 0$:

$$\dot{\tilde{c}}^R = (\rho+\xi)\,\tilde{c}^R - \left[\theta(\rho+\xi)+\xi\gamma(1-\theta)\right]\tilde{h}^R.$$

Then together with the time derivative of (4.20) I find the following system of dynamic equations

$$\begin{bmatrix} \dot{\tilde{h}}^R \\ \dot{\tilde{c}}^R \end{bmatrix} = \begin{bmatrix} -\xi & \xi \\ -\left[\theta(\rho+\xi)+\xi\gamma(1-\theta)\right] & \rho+\xi \end{bmatrix} \begin{bmatrix} \tilde{h}^R \\ \tilde{c}^R \end{bmatrix}.$$

From (4.23) and (4.25) I have $\dot{\tilde{h}}^R = -\xi\lambda\tilde{h}^R$ and $\dot{\tilde{c}}^R = -\xi\lambda\tilde{c}^R$, so

$$0 = \begin{bmatrix} -\xi\left(1-\lambda^{opt}\right) & \xi \\ -\left[\theta(\rho+\xi)+\xi\gamma(1-\theta)\right] & \rho+\xi\left(1+\lambda^{opt}\right) \end{bmatrix} \begin{bmatrix} \tilde{h}^R \\ \tilde{c}^R \end{bmatrix},$$

and λ^{opt} is implicitly determined by

$$R^{opt}\left(\lambda^{opt}\right) = (\theta - 1)\left[\rho + \xi\left(1-\gamma\right)\right] + \lambda^{opt}\left(\rho + \xi\lambda^{opt}\right) = 0. \tag{4.B.4}$$

First, I have $R^{opt}(0) < 0$ and $dR^{mc}/d\lambda > 0$ for $\lambda > 0$, which implies there exists some $\lambda^{opt} > 0$ that satisfies (4.B.4). Next, I can show $R^{opt}(\lambda^{mc}) = -(\theta-1)\,\xi\left[\gamma + \frac{\theta}{\eta-1}\right]$ which is positive. Hence, I can conclude that $\lambda^{opt} < \lambda^{mc}$. Finally $R^{opt}(1-\gamma) = (\theta-\gamma)\left[\rho + \xi\left(1-\gamma\right)\right]$ while $R^{opt}\left(\lambda^{pc}\right) = (\theta-\gamma)\left(\theta-1\right)\xi$. Then if $\gamma = \theta$, we have $\lambda^{opt} = 1+\theta = \lambda^{pc}$. If $\gamma < \theta$, we must have $\lambda^{opt} \in (1-\theta, 1-\gamma)$ while if $\gamma > \theta$, $\lambda^{opt} \in (1-\gamma, 1-\theta)$.

The closed-form solution for λ^{opt} then reads

$$\lambda^{opt} = \frac{\sqrt{\rho^2 - 4\xi\left(\theta-1\right)\left[\rho+\xi\left(1-\gamma\right)\right]} - \rho}{2\xi}.$$

□

4.C Discretized model

Instead of discretizing the pricing rules (4.10) and (4.30), I rederive them by solving the discrete time model 'bottom up'. In discrete time, (4.1)-(4.2) and (4.4)-(4.8) still apply. The equation of motion for habits is replaced by

$$h_{it+1} = \xi c_{it} + (1-\xi)\,h_{it}, \tag{4.C.1}$$

where the use of time subscripts indicates we now deal with the discrete-time version of the model. Under perfect competition, $p_{it} = \delta_{it}\tau_{it}$ still. Under monopolistic competition, the producer maximizes $\Pi_{it} = \sum_{\nu=t}^{\nu=\infty}(1+\rho)^{-(\nu-t)}\,c_{i\nu}\left(p_{i\nu} - \delta_{i\nu}\tau_{i\nu}\right)$, subject to (4.7) and (4.C.1). This gives the following pricing rule:

$$p_{it} = \delta_{it}\tau_{it}\frac{\eta}{\eta-1}\left[\frac{1 - \frac{1-\xi}{\rho+\xi}\frac{\delta_{it+1}\tau_{it+1}-\delta_{it}\tau_{it}}{\delta_{it}\tau_{it}}}{1 + \frac{\xi}{\rho+\xi}\frac{\theta}{\eta-1}\frac{p_{it+1}}{p_{it}}\frac{c_{it+1}}{h_{it+1}} - \frac{1-\xi}{\rho+\xi}\left(\frac{p_{it+1}-p_{it}}{p_{it}}\right)}\right]. \tag{4.C.2}$$

The policymaker instead maximizes $W_t = \sum_{\nu=t}^{\nu=\infty}(1+\rho)^{-(\nu-t)}\,U_\nu$, subject to (4.1)-(4.2), (4.4)-(4.6) and (4.C.1). This gives the optimal price for good i

$$p_{it} = \delta_{it}\mu_{L_t}\left[\frac{1 - \left(\frac{1-\xi}{\rho+\xi}\right)\left(\frac{\delta_{it+1}\mu_{L_{t+1}}-\delta_{it}\mu_{L_t}}{\delta_{it}\mu_{L_t}}\right)}{1 + \frac{\xi}{\rho+\xi}\frac{p_{it+1}}{p_{it}}\frac{c_{it+1}}{h_{it+1}}Z_{t+1} - \left(\frac{1-\xi}{\rho+\xi}\right)\frac{p_{it+1}-p_{it}}{p_{it}}}\right], \tag{4.C.3}$$

with

$$Z_{t+1} \equiv \left[\frac{\theta}{\eta - 1} - \left(\gamma + \frac{\theta}{\eta - 1} \right) \left(\frac{h_{it+1}}{H_{t+1}} \right)^{\frac{\eta-1}{\eta}} \left(\frac{c_{it+1}}{C_{t+1}} \right)^{-\frac{\eta-1}{\eta}} \right]. \tag{4.C.4}$$

A comparison of (4.C.2) and (4.C.3)-(4.C.4) to (4.10) and (4.30)-(4.32) respectively reveals two differences between the continuous and discrete time pricing rules. First, in continuous time, the denominator features the instantaneous ratio of good-specific consumption to habits, while in discrete time this is the ratio at time $t+1$, multiplied by the ratio of time $t+1$ to time t good-specific prices. Similarly, for the discrete-time optimal price (4.C.3), C and H are evaluated at time $t+1$, while in continuous time we have $C(t)$ and $H(t)$. This can be explained as follows. In continuous time, the habit adjustment occurs instantaneously. Hence to evaluate the value of the habit, instantaneous consumption, habits and prices are relevant. In discrete time, it is the next-period habit that adjusts, and thus next-period consumption, habit and prices that are relevant to determine the value of investing in the habit. In both cases, the value of the habit is then evaluated relative to current prices.

Second, in the discrete time pricing rules, the future change in taxes and prices are multiplied by an additional $1 - \xi$. This is intuitive. In the discrete time model, if $\xi = 1$, habits fully adjust from one period to another and the decision maker only needs to know the value of habits one period ahead. Hence, for $\xi = 1$, future changes in the value of the habit, captured by the change in prices (net of taxes), becomes irrelevant and drops out. In the continuous time pricing rules, (4.10) and (4.30), this full adjustment from one *instant* to another occurs if $\xi \to \infty$. Here again, future price and tax changes drop out. Note that where any $\xi \geq 0$ can be rationalized in the continuous time model, in the discrete time model only $\xi \in [0, 1]$ are sensical.

To obtain numerical results I use the Dynare package for Matlab. The number of periods for full convergence was set to 300 months. A doubling to 600 periods did not noticeably alter results.

Chapter 5

A SIMPLE FORMULA FOR THE SOCIAL COST OF CARBON

Abstract

The social cost of carbon (SCC) is the monetized damage from emitting one unit of CO_2 to the atmosphere, often obtained from computational Integrated Assessment Models (IAMs). We develop a closed-form formula that approximates the SCC for a general economy, and then explore the capacity of the analytical approach to capture the key SCC drivers and thus to replicate the results of the deterministic IAMs. The formula explains the parameter-driven SCC variation of a mainstream IAM without a systematic bias. The sensitivity analysis identifies and measures the performance limits of the closed-form formulas. We then use the analytic formula to structurally interpret a distribution of SCCs from deterministic IAMs, and develop an analytical breakdown and quantification of how different sets of parameters contribute to the SCC distribution. This allows the user of the formula to evaluate where particular parameter choices tend to place the resulting SCC outcome in the distribution of outcomes for the universe of deterministic IAMs.

This chapter is based on joint work with Reyer Gerlagh and Matti Liski, which is published as Van den Bijgaart et al. (2016)

5.1 Introduction

The Social Cost of Carbon (SCC) monetizes the damage from releasing a ton of CO_2 to the atmosphere today. The monetization of damages is essential for the determination of optimal climate policies; pricing carbon according to the SCC provides the correct economic incentive for reducing current emissions. The SCC can be obtained by using computational Integrated Assessment Models (IAMs) that connect the global carbon cycle and temperature dynamics to a global economy description to assess the marginal welfare costs of emissions. There are several widely used IAMs.[1] While the IAMs overarch the contributions from various disciplines in climate-change research, they are not easily accessible to policymakers and researchers in general.[2] There are various systematic assessments of the assumptions in the IAMs and their effects on outcomes (Anthoff and Tol, 2013; Hope, 2008; Nordhaus, 2008; Weyant et al., 2006). The assessments show that higher climate sensitivity, higher estimates of damages for given temperature change, and lower discount rates generally lead to higher estimates for the SCC. They do not, however, solve a fundamental problem: to the wider audience, the IAMs remain a black box and the resulting SCC is a number accepted or rejected on the basis of trust or distrust in the models and their developers (Kelly and Kolstad, 1999b). Newbold et al. (2013) build a parsimonious and transparent IAM to help the user in understanding "how the SCC is likely to respond to alternative assumptions and input parameter values." Still, the user needs to ask the authors for the model, study it, run it, and analyze the outcomes.[3]

Golosov et al. (2014) derive an analytical formula for the SCC in an integrated assessment model, based on specific assumptions such as logarithmic utility and climate-change damages proportional to output and exponential in the atmospheric CO_2.[4] Gerlagh and Liski (2012) add a more comprehensive description of the cli-

[1] Most notable IAMs include DICE (Nordhaus, 1992; 2008), CETA (Peck and Teisberg, 1992), PAGE (Hope et al., 1993), MERGE (Manne and Richels, 2005), FUND (Tol, 2005), MIT ISGM (Webster et al., 2003), R&DICE (Nordhaus and Boyer, 2000).

[2] The proof of the pudding is in the eating. Here we consider accessibility as revealed through use by others. Most policymakers (need to) rely on supporting researchers who can run IAMs for policy assessments. Some IAMs are considered relatively simple, but only DICE (Rabin, 1992) is sufficiently simple and comprehensive enough to have attracted a large group of users in the research community. R&DICE and FUND have publicly available descriptions and full source codes. R&DICE is used by a few researchers, but, to our knowledge, Ackerman and Munitz (2012) are the only researchers who used FUND, other than the developers. Learning to work with a model developed by someone else typically requires a very long learning time. Ackerman and Munitz (2012) reported on the results of their difficult process of running someone else's model; they required help by the developers.

[3] The current literature considers the existing simple models, such as DICE, as the furthest point to which one can get towards practical and accessible tools for assessment, away from large-scale 'black box' models, without sacrificing what is seen to be the essential structure for the climate-economy interactions.

[4] See Barrage (2014) for a sensitivity analysis of the assumptions.

mate system and associated temperature-change delays, and study the implications of the formula for the optimal policies in a general-equilibrium context with time-inconsistent preferences. In the current chapter, we build on this emerging analytical literature to develop a closed-form SCC formula that approximates a general economy, and to provide a systematic testing of the formula. The objective is to explore the capacity of the analytical approach to capture the key SCC drivers and thus to replicate the results of the deterministic IAMs.

To evaluate the "internal validity" of the formula we test its performance against a mainstream numerical IAM (DICE, Nordhaus, 2008).[5] Using a conservative sampling of the IAM parameters, we find that, on average, the formula explains the parameter-driven variation in the IAM SCC: the eight central parameters that enter the formula predict the IAM outcome, which depends on 14 parameters, without quantitatively significant systematic bias. The largest gaps in outcomes are associated with situations where climate damages are either strongly concave or convex, and, at the same time, the discount rate takes extreme values (low or high). The reasoning behind the deviations helps in understanding and measuring the performance limits of the closed-form formula.[6]

To consider the "external validity" of the formula, we generate a distribution for the SCC from the underlying parameter distributions derived from the literature. The resulting distribution compares well with the existing distribution of SCC estimates produced by a sample of numerical IAMs (Tol, 2009). Since the formula is a structural interpretation for the SCC distribution, we can develop an analytical breakdown and quantification of how different sets of parameters contribute to the SCC distribution. The right-skewness of the SCC distribution has little to do with the carbon cycle and temperature delay parameters; damages and the determinants of discounting have a large contribution. In addition, due to the non-depreciating climate boxes, some climate impacts are permanent, fattening the tail of the SCC distribution when discounting falls towards zero. Importantly, analytical models without a multi-box description of the climate system ignore this tail-fattening effect.

In contrast with Golosov et al. (2014) and Gerlagh and Liski (2012), we derive the SCC in closed-form for a general economy whose development is approximated by a balanced-growth path. The approximation allows extending the formula to cover elements that have been noted important in the literature: non-unitary elasticity of marginal utility (Jensen and Traeger, 2014); climate-change damages increasing more or less than proportionally with income (Hoel and Sterner, 2007; Traeger, 2014); a

[5]Because of its public availability, conciseness, transparent documentation, and middle-of-the-road assumptions, we choose DICE (Nordhaus, 2008) for testing the accuracy of the formula. We extend DICE with damages that grow more or less than proportional with output, see footnote 22.

[6]In spirit, the approach is similar as in Nordhaus (1991); he considers a steady-state approximation.

climate-response function based on a more comprehensive emissions-temperature model (Gerlagh and Liski, 2012). The formal derivation thus requires a balanced-growth path; then, we test how the formula performs outside the balanced growth path.

The current study should be understood as an investigation into the basic mechanisms of the numerical IAMs; we do not consider climate policy making under uncertainty or learning (e.g., Crost and Traeger, 2013; Keller et al., 2004; Kelly and Kolstad, 1999a; Leach, 2007). Thus, the formula, as currently expressed, cannot provide guidance on how the optimal polices should develop over time when new information about the climate-economy interactions arrive (e.g., Gerlagh and Liski, 2014; Lemoine and Traeger, 2014), or how attitudes towards uncertainty might shape the current SCC (Jensen and Traeger, 2014).[7,8]

Instead, the objective is to link the predictions of the commonly used deterministic simulation models and those of the analytical representations for the current carbon price. With this focus in mind, the formula seeks to bring the knowledge that has been accumulated in the climate research, to the domain of analytical economics and further democratize it: by use of our formula, any reader can perform his or her own informed assessment about the SCC.[9] Given its performance, the formula can be seen as a useful policy tool. Without the need for assistance in running an IAM, it allows the policymaker to assess the sensitivity of the SCC estimate to climate sensitivity, climate-change damages, and discounting. That is, the formula directly shows an estimate for the SCC, given the choices for the set of fundamental parameters. Moreover, since we have evaluated how different parameter sets contribute to the SCC distribution, the user of the formula has tools for discussing where particular parameter choices tend to place the resulting SCC outcome in the distribution of outcomes for the universe of deterministic IAMs. For example, using median values for the carbon cycle parameters does not tend to place the estimate above or below the mean for the SCC outcomes; however, the median for damages places the output clearly below the mean SCC.

The chapter is structured as follows. In Section 5.2, we introduce the climate-economy decision problem, and derive, without specifying the structure of the economy, a general expression for the SCC. We build on optimization, but the SCC expres-

[7] Rezai and van der Ploeg (2016) also take the simple formula from Van den Bijgaart et al. (2013) to elaborate its validity under various extensions. Their paper is complementary to ours because, in particular, they use the formula to assess the time paths of the SCC in comparison with those produced by a benchmark model. They find minimal welfare losses if one applies the simple rule as the basis for the climate policy over time.

[8] The impact of short-term fluctuations on the choice of the optimal policy instrument has been considered, for example, in Hoel and Karp (2001; 2002) and in Karp and Zhang (2006).

[9] The reader can fill in the parameters and see the results immediately through an Excel file available through http://www.sciencedirect.com/science/article/pii/S0095069616000061.

sion turns out to be valid irrespective of whether the economy follows the optimal policy or not. The result allows us to obtain the closed-form SCC that approximates the general economy. We then run two types of experiments with the formula. In Section 5.3, we perform the sensitivity analysis of the formula against an extended version of DICE. In Section 5.4, we generate the SCC distribution and elaborate the sources of variation in the distribution. Section 5.5 concludes.

5.2 Model

5.2.1 Base model

We derive the SCC expression first for a general climate-economy model.[10] There is a representative consumer who maximizes the stream of future aggregate utilities, discounted at rate ρ. Population is denoted by L. Output F depends on capital K, emissions E, and the global average surface temperature T, and on time t that may capture technological development. Output is used for consumption C, replacement of depreciated capital $\delta_K K$, or net investments. Emissions add to the atmospheric CO_2 stock S, which depreciates at rate δ_S. Here, we define S as the CO_2 stock over and above the pre-industrial level of CO_2. Temperatures adjust at rate ε to their physical long-run equilibrium level $\varphi(S)$.

$$\max \int_0^\infty e^{-\rho t} LU(C/L)dt, \tag{5.1}$$

$$C + \dot{K} = F(K, E, T; t) - \delta_K K, \tag{5.2}$$

$$\dot{S} = E - \delta_S S, \tag{5.3}$$

$$\dot{T} = \varepsilon \left(\varphi(S) - T\right). \tag{5.4}$$

A dot denotes a time derivative. We suppress time scripts for variables, but keep the time script for production $F(.;t)$, to remind us that we assess climate change in a context of continued economic growth through technological change.[11]

The model assumes perfect foresight, and there is no uncertainty within the

[10] Golosov et al. (2014) provide formal conditions under which a simple formula is valid in a general equilibrium framework; the formula here deviates from their result as we present a richer description of damages depending on temperature change and income, time lags in climate change, and a non-unitary elasticity of marginal utility.

[11] Most IAMs assume implicitly or explicitly that both costs and benefits of emissions reductions are small compared to the economic benefits of technological progress over the relevant time scale (Azar and Schneider, 2002; Gerlagh and Papyrakis, 2003). That is, the decrease in $F(.)$ when emissions E drop to zero, or when temperatures increase by 3 degrees Celsius, is typically very small compared to the increase in F brought by innovation as captured through time t.

model; we assess the sensitivity of the SCC with respect to the parameters and do not assess the effect of within-the-model uncertainty on the policies. Demography, innovation and income growth may respond to environmental conditions, we neglect such feedback mechanisms and assume an exogenous innovation and population growth path. Emissions are endogenously determined; however, it is not obvious if changes in emissions are important for the level of the social cost in comparison to the contribution of the key parameter choices. We quantify the effect of policy choices on the SCC in our analysis.

We thus assume a continuous physical climate-change process. We seek to include a meaningful impulse-response function that connects CO_2 emissions to atmospheric concentrations, and concentrations to temperature rise. For exposition, we postpone the full impulse-response to Section 5.2.3. We abstract from thresholds or tipping points where the dynamics of the carbon cycle or temperature adjustment change dramatically; see Lemoine and Traeger (2014) for further analysis.

Consider now the shadow-cost variables p, τ, χ for state equations (5.2)-(5.4), respectively. We interpret all shadow costs such that they take a positive value. That is, τ measures the marginal-utility weighted social cost of carbon – dividing by marginal utility, gives the monetized SCC that, when the optimal policy is implemented, equals the marginal product of energy use, $\partial F/\partial E = SCC$. Variable χ measures the current-value marginal cost of an increase in temperatures. In Appendix 5.A, we provide the Hamiltonian for the problem (5.1)-(5.4), and describe the first-order conditions in (5.A.2)-(5.A.6). These conditions include for C, E, K, S, T:[12]

$$\frac{\partial U}{\partial C} = p, \tag{5.5}$$

$$p\frac{\partial F}{\partial E} = \tau, \tag{5.6}$$

$$\dot{p} = p\left(\rho - \frac{\partial F}{\partial K} + \delta_K\right), \tag{5.7}$$

$$\dot{\tau} = (\rho + \delta_S)\,\tau - \frac{\partial \varphi}{\partial S}\varepsilon\chi, \tag{5.8}$$

$$\dot{\chi} = (\rho + \varepsilon)\,\chi + p\frac{\partial F}{\partial T}. \tag{5.9}$$

We note that (5.5) and (5.7) determine the optimal capital-investment versus consumption decision, while (5.8) and (5.9) are accounting equations that define the net present value of future marginal damages. The optimal climate policy is implemented through (5.6), defining $\partial F/\partial E = SCC = \tau/p$. But note that we can cal-

[12] Note that $\partial F/\partial T < 0$, so that the last term in (5.9) is negative, similar to the last term in (5.8).

culate the SCC also for non-optimal climate policies. For example, if we substitute $\partial F/\partial E = 0$ for (5.6), and maintain (5.5), (5.7)-(5.9), we find τ/p as the SCC for the business-as-usual scenario.

For notational convenience, we write η for the (negative) elasticity of marginal utility, g for per capita consumption growth rate, r for the net rate of return on capital, and $R(s;t)$ for the consumption discount factor between time t and s:

$$\eta \equiv -\frac{C\frac{\partial^2 U}{\partial C^2}}{L\frac{\partial U}{\partial C}}, \tag{5.10}$$

$$g \equiv \frac{\dot{C}}{C}, \tag{5.11}$$

$$r \equiv \frac{\partial F}{\partial K} - \delta_K, \tag{5.12}$$

$$\frac{\dot{R}}{R} \equiv -r, \tag{5.13}$$

$$R(s;t) \equiv R(s)/R(t). \tag{5.14}$$

We normalize $R(0) = 1$, so that we can write for shorthand $R(s) \equiv R(s;0)$. Substituting the time derivative of (5.5) into (5.7) gives then the Ramsey rule:

$$r = \rho + \eta g. \tag{5.15}$$

Using the notation above, we can rewrite (5.8) and (5.9) to derive an explicit formula for the SCC at time zero (see Appendix 5.A for details) as the net present value of marginal damages:

$$SCC(0) = -\int_0^\infty e^{-\delta_S t} R(t) \frac{\partial \varphi}{\partial S}(t) \int_t^\infty \varepsilon e^{\varepsilon(t-s)} R(s;t) \frac{\partial F}{\partial T}(s) ds\, dt. \tag{5.16}$$

This expression for the SCC continues to hold even when the policy choices are not optimal.[13]

5.2.2 Adding structure

We follow most of the IAM literature and assume that the relation between atmospheric CO_2 concentrations and equilibrium temperatures can be described through

[13]Equation (5.16) is an accounting equation therefore it must hold for all optimal and non-optimal paths. Yet, obtaining a well-defined non-optimal path is not straightforward. Rezai et al. (2012) note that, in the representative agent framework, it is inconsistent to ignore the carbon price and, at the same time, to anticipate and internalize the impacts of capital investments, through induced emissions and climate change, on future production possibilities.

a logarithmic curve:

$$\varphi(S; c, m) = c\frac{\ln(1 + S/M)}{\ln(2)}, \tag{5.17}$$

where c is the climate sensitivity parameter, that is, the temperature rise at a doubling of atmospheric CO_2, and m is the pre-industrial atmospheric CO_2 level.

The net output is gross output minus climate damages. Climate damages are assumed to increase with output changes, with elasticity ξ, and to increase with temperatures, with elasticity ψ:

$$F(K, E, T; t) = Y(K, E; t)\left[1 - \omega T^{\psi}\left(\frac{Y(K, E; t)}{L\bar{y}}\right)^{\xi - 1}\right], \tag{5.18}$$

where $Y(.)$ is gross output before subtracting climate damages, and $\bar{y}$ is the reference per capita income level at which a one-degree temperature rise leads to relative damages ω.

The above functional form assumes that the costs of climate change are a smooth function of income, population, and temperature rise.[14] Most IAMs assume that damages are proportional to income. If the value of ecosystems lost by climate change increases more than proportional to income, $\xi > 1$, the cost of climate change increases and we expect a higher SCC (Hoel and Sterner, 2007; Sterner and Persson, 2008). On the other hand, if economic growth allows society to cope more easily with the consequences of climate change, we obtain $\xi < 1$, and we expect a lower SCC. Another typical assumption in IAMs is that damages are quadratic in temperatures, but some researchers suggest a higher or lower order damage function (e.g., Kopp and Mignone, 2013). Below we use quadratic costs as the median value for ψ; in the experiments we consider $1 \leq \psi \leq 4$.

Considering a climate system close to a stationary state, that is $T = \varphi(S)$, it is not immediately evident whether output damages are concave or convex in S – damages are given by a convex function of temperatures which in turn depend on S through a concave function. Indeed, for costs that rise quadratically with temperature change, $\psi = 2$, the composite dependence of damages on concentrations is close to linear over the domain where S is between 400 and 550 ppm:[15]

[14] Theoretically, (5.18) allows for net output to become negative. The purpose of this formulation is that it gives a simple analytical result. We compare the analytical results with those from a numerical model where damages are formulated such that output never becomes negative.

[15] At the time of writing CO_2 concentrations are about 400 ppm, which compared with a pre-industrial stock of approximately 275 ppm gives $S/m = (400 - 275)/400 \approx 0.45$. The approximation comes from $(1 - \ln(1.45)/\ln(2))2/(1–0.45) = 1.3$.

$$\frac{\partial\left(c\frac{\ln(1+S/M)}{\ln(2)}\right)}{\partial S} \approx 1.3c^2/m. \tag{5.19}$$

Considering that the expected concentrations for the coming decades are in the range between 400 and 550 ppm, we use the average slope of the curve for our formula, and postulate the same approximation for other values of ψ. Writing $D = T^\psi$, we approximate the damage response as

$$\frac{\partial D}{\partial S} \approx 1.3c^\psi/m, \tag{5.20}$$

$$\frac{\partial F}{\partial D} = -\omega\left(\frac{Y(t)}{L\bar{y}}\right)^{\xi-1} Y(t), \tag{5.21}$$

$$\frac{\partial F}{\partial T}\frac{\partial \varphi}{\partial S} = \frac{\partial F}{\partial D}\frac{\partial D}{\partial S} \approx -1.3\frac{\omega c^\psi}{m}\left(\frac{Y(t)}{L\bar{y}}\right)^{\xi-1} Y(t). \tag{5.22}$$

We foresee the following shortcoming of approximations (5.20)-(5.22). Consider an increasing temperature path. The formula assumes that marginal damages are constant over the range 400-550 ppm, but when ψ is high (> 2), marginal damages are increasing with temperatures. Thus, the formula understates marginal damages in the long run where the temperatures are high; it overstates marginal damages in the short run where the temperatures are low. When the discount rate ρ is small, the long-run understatement of the damages becomes important and the formula SCC will tend to return a too low value. For high discount rates, the formula's overstatement of the shorter-term damages receives more weight, and then the formula tends to overshoot the true SCC. When ψ is low (< 2), damages are concave and the approximation leads to opposite effects: shorter-term damages are understated and the longer-term damages are overstated. That is, we conjecture the formula to work best for values of ψ around 2, and a potential structural bias in the SCC formula when both discounting and the elasticity of damages with respect to the temperature are far from average.

To approximate the development of the economy, we consider a balanced growth path with constant savings rate, where the economy grows at constant growth rate $g + l$, with g the per-capita income growth and l the population growth rate. The climate-economy models do not typically satisfy the balanced-growth assumptions that effectively require all technological change to be labor-augmenting (Uzawa, 1961). Since the true economy does not follow a balanced growth path, the formula is meant to be an approximation to be tested.[16] Technically, however, we can use

[16] Note that the closed-form formulas can also be obtained without the balanced growth assumption

formula (5.16) to obtain the SCC for any growth path since the formula basically is an accounting equation.

Balanced growth ensures that the discount factor R decreases at constant rate $\rho + \eta g$. In the definition of the SCC (5.16), within the integrals we also find marginal damages, $\frac{\partial F}{\partial T}\frac{\partial \varphi}{\partial S}$, which equation (5.22) tells us grow at rate $\xi g + l$. We define σ the "climate discount rate", as the decrease in the value we attribute to future damages, corrected for the tendency of future damages to increase. Technically, σ is the negative overall growth rate of the terms within the integrals of (5.16), excluding the atmospheric CO_2 depreciation δ_S and temperature adjustment ε:

$$\sigma = \rho + (\eta - \xi)\, g - l. \tag{5.23}$$

Proposition 5.1. *Consider the economy (5.1)-(5.4), approximated by a balanced growth path with constant population growth, and constant per capita income growth. Assume damages that have a constant elasticity with respect to temperatures ψ and with respect to output ξ. The approximate social costs of carbon, as defined by expression (5.16), is then given by the reduced form formula:*

$$SCC = \frac{1.3\omega c^{\psi}}{m}\frac{1}{\delta_S + \sigma}\frac{\varepsilon}{\varepsilon + \sigma}\left(\frac{Y}{L\bar{y}}\right)^{\xi - 1} Y, \tag{5.24}$$

where ω, c, ψ, m, δ_S, ε, are the primitives, Y is the current output, and σ depends on the primitives ρ, g, l, η , ξ, as in (5.23).

Proof. The proof follows from substituting the growth rates into (5.16) which gives

$$SCC(0) = \frac{1.3\omega c^{\Psi}}{m}\left(\frac{Y(0)}{L\bar{y}}\right)^{\xi-1} Y(0)\int_0^{\infty} e^{-(\delta_S+\sigma)t}\int_t^{\infty} \varepsilon e^{-(\varepsilon+\sigma)(t-s)} ds\, dt \tag{5.25}$$

$$= \frac{1.3\omega c^{\Psi}}{m}\left(\frac{Y(0)}{L\bar{y}}\right)^{\xi-1} Y(0)\frac{1}{\delta_S + \sigma}\frac{\varepsilon}{\varepsilon + \sigma}. \tag{5.26}$$

□

There are no restrictions on σ to ensure that it is strictly positive. If σ is sufficiently negative, the SCC is without bound.[17] In this situation however, the simple formula also loses relevance. If the SCC grows very large, future abatement options become

under specific structures for the preferences and technologies (Golosov et al., 2014).

[17]For (5.23), this would be the case either if $\sigma < -\delta_S$ or $\sigma < -\varepsilon$. In Section 5.2.32.3 we consider a refinement with more detailed climate dynamics. As these dynamics account for the fact that a very small share of emissions remain in the atmosphere for more than a 1000 years, the SCC is without bound already for $\sigma = 0$.

important.[18] Note also that, as long as information regarding the appropriate parameter values is not updated, the SCC is expected to grow at the rate of income, Y, although we do not intend to consider SCC time paths in this chapter.

An intricate part of the formula (5.24) is in the last two terms. The first term, $1/(\delta_S + \sigma)$, measures the economic lifetime of atmospheric CO_2. Both a rapid carbon depreciation, through high δ_S, and a high discount rate, σ, reduce the economic lifetime of CO_2. When there is no discounting, $\sigma = 0$, and $1/\delta_S$ measures the mean lifetime of atmospheric CO_2, which is about 50 to 100 years. For a 2 per cent annual climate discount rate, the economic lifetime of atmospheric CO_2 drops to a level between 1/(.02+.02)=25 and 1/(.01+.02)=33 years.

The second term, $\varepsilon/(\varepsilon + \sigma)$, measures the carbon price discount related to the delay of damages caused by the earth's heat inertia. An immediate full temperature adjustment, $\varepsilon \to \infty$, results in no discount. Slower adjustment implies that the impact of increases in atmospheric CO_2 is more distant, which reduces the carbon price. For a typical 2 to 4 percent annual temperature adjustment speed, and an annual 2 per cent climate discount rate, the delay discount factor lies between $.02/(.02 + .02) = 0.5$ and $.04/(.02 + .04) = 0.67$. The delay discount factor can be approximated by a temperature lag. Suppose temperature change is lagged by N years after the corresponding change in the atmospheric CO_2 stock, and the discount rate is σ, then the lag results in a discount factor $e^{(-\sigma N)}$ for the net present value of damages. If we substitute $N = 25$ years, and consider a discount rates of 2% per year, we find that $X = e^{-0.5} = 0.61$, which is within the range 0.5-0.67 stated above. A simplified interpretation of the 2 to 4 percent temperature adjustment speed is thus that temperature change lags about 25 years behind atmospheric carbon dioxide concentrations.

Jointly, the terms $1/(\delta_S + \sigma)$ and $\varepsilon/(\varepsilon + \sigma)$ weigh the persistence and delay of climate change; they cumulate the damage response over time, with weights decreasing exponentially at rate σ. Through these terms the SCC formula approximate the connection between emissions and damages in the IAMs.

5.2.3 Extension of the climate dynamics

The simple model assumes a single depreciation factor for the atmospheric CO_2 and a single temperature adjustment speed. We use the simple model in testing the formula's performance against DICE in Section 5.3. In this subsection, we extend the

[18]For a high SCC value, it becomes profitable to capture CO_2 from the air. The trade-off is then not so much between future benefits of preventing climate change and present costs of reducing emissions, but between the latter and the future costs of CO_2 air capture. The, the policy will be determined by the lowest-cost abatement strategy instead of the tradeoff between emission cost and benefits.

simple model to allow for a more flexible representation of the carbon cycle and temperature adjustments.[19] The extension allows us to quantitatively assess the contribution of climate system parameters to the carbon price distribution in Section 5.4. Thus, the simple and extended models have different roles in the quantitative exercise; the former identifies the key parameters necessary for matching the DICE outcomes, and the latter provides an extension connecting to the wider literature. Moreover, the extension shows that the simple climate description used in the previous Section, by assumption, puts a bound on the contribution of discounting to the carbon price.

In the extension, the atmospheric CO_2 depreciation is described through a set of impulse response functions with exponential decays, where each function is labeled by $i \in I = \{1, \ldots, n\}$, and a_i is the share of emissions with decay rate δ_{S_i}, as in Maier-Reimer and Hasselmann (1987) and Hooss et al. (2001):

$$S(t) = \sum_{i \in I} S_i(t), \tag{5.27}$$

$$\dot{S}_i(t) = a_i E(t) - \delta_{S_i} S_i(t). \tag{5.28}$$

In Appendix 5.5, we present 16 carbon-cycle models as proxied by Joos et al. (2013) through an ensemble of exponential decay functions (see Figure 5.C.1). All models show a rapid decay in the first decade, and most models suggest that a substantial fraction of CO_2 remains in the atmosphere after 1000 years.[20]

In analogy to the atmospheric carbon depreciation that is represented through a multi-response function, temperature change can be represented through a multi-temperature response function (Caldeira and Myhrvold, 2013). The more general concentration-temperature response function then becomes

$$T(t) = \sum_{j \in J} T_j(t). \tag{5.29}$$

$$\dot{T}_j = \varepsilon_j \left(b_j \varphi(S; c, m) - T_j \right), \tag{5.30}$$

with $\sum_{j \in J} b_j(t) = 1$. We can now establish

Proposition 5.2. *For the same assumptions as in Proposition 5.1, but with a multi-response function for atmospheric CO_2 and temperature change, the social costs of carbon is given by*

[19]We have also considered other extensions while maintaining a closed form solution. For example, we can allow for a declining, instead of exponential, population growth. However, this extension turned out to be less important for the quantitative evaluation than the climate system description.

[20]The earth system models suggest that the fraction remaining in the atmosphere increases with cumulative emissions. Such can increase the SCC, an effect that we, as most IAMs, do not account for.

the reduced-form formula:

$$SCC = \frac{1.3\omega c^{\Psi}}{m} W(\sigma, \mathbf{a}, \delta_S) X(\sigma, \mathbf{b}, \boldsymbol{\varepsilon}) \left(\frac{Y}{L\bar{y}} \right)^{\xi - 1} Y, \tag{5.31}$$

$$W(\sigma, \mathbf{a}, \delta_S) = \sum_{i \in I} \frac{a_i}{\sigma + \delta_{S_i}};\ X(\sigma, \mathbf{b}, \boldsymbol{\varepsilon}) = \sum_{j \in J} \frac{b_j \varepsilon_j}{\sigma + \varepsilon_j}. \tag{5.32}$$

The formula is derived in a similar manner as equations (5.22) and (5.23) for the one-box model. For interpretation, note that $W(.)$ measures the economic life-time of emissions. When the climate discount rate approaches zero, $\sigma \to 0$, $W(.)$ becomes

$$W(0, \mathbf{a}, \delta_S) = \frac{a_1}{\delta_{S_1}} + ... + \frac{a_n}{\delta_{S_n}}. \tag{5.33}$$

Thus, the economic life-time of CO_2 becomes the physical life-time of CO_2. In particular, if a share of emissions, say $a_i > 0$, depreciates slowly, $\delta_{S_i} \to 0$, term $W(.)$ becomes unbounded. This is an important difference to the simple model where, with vanishing discounting, the economic life-time of CO_2 converges to $1/\delta_S$. See also Gerlagh and Liski (2012) for further discussion. In Section 5.4, we quantify how the climate system uncertainty, in the form of very low possible decay rates in some parts of the climate system, together with low discounting, translates into a tail-fattening effect in the SCC distribution.

Similarly, $X(\sigma, \mathbf{b}, \varepsilon)$ is the discount factor associated with the slow temperature adjustment. We postpone the further analysis of this factor to Section 5.4.

5.3 Experiment I: testing the formula

We now evaluate quantitatively how well the formula in Proposition 5.1 predicts the SCC of DICE (Nordhaus, 2008).[21] The experiment is conducted by assuming distributions for 14 key climate and economic parameters entering DICE, and then sampling 100,000 draws for the parameter vector. Each draw defines also the subset of parameters that enter our formula. In the analysis, our dependent variable is the difference between the formula SCC and the DICE SCC (or, the SCC gap); the independent variables are the parameter realizations. We evaluate the contributions of various parameters to the SCC gap.

[21] DICE is the single-most used IAM. To the knowledge of the authors, DICE is the only IAM that satisfies three conditions: (i) the source code is publicly available and can be run easily, (ii) for each major version of the model, an integrated and complete model description is publicly available, (iii) it is convenient in use. For other IAMs, either the model code is unavailable, or the model descriptions are scattered over various publications, or the model is built using software for which few researchers have the required skills.

5.3.1 Sampling procedure

The 14 parameters for DICE describe the climate sensitivity, damage severity, the structure of time preferences, population growth, income growth, baseline emissions, and abatement costs.[22] The full list of the parameters is provided in the Appendix (Table 5.B.1), together with the quantitative values that we obtain from the literature. Specifically, we use the values in the literature to present each parameter by a right-skewed distribution, taken to be log-normal and distinct for each parameter. This set of log-normals defines our primitive parameter distributions, used also in the analysis of Section 5.4. However, in this Section, for the purpose of setting a conservative test for the formula's performance, we want to oversample the extreme parameter realizations far from the median. To this end, for each parameter, we transform the primitive log-normal to a log-uniform distribution, while matching the median of the original distribution; effectively, the sampling is from a uniform distribution applied to the logarithm of the parameters. This sampling procedure oversamples the corners of the original parameter space, compared to the primitive distribution.[23]

There are eight parameters that enter our formula: climate sensitivity (c), relative damages at 3 Kelvin temperature increase (ω), damage-temperature elasticity (ψ), damage-output elasticity (ξ), elasticity of marginal utility (η), time discount rate (ρ), consumption growth rate (g), and population growth rate (l).[24,25] To save on the dimensions of the parameter space, we do not consider variations in the parameters of the carbon cycle when testing the performance of the formula; for the contribution of the "natural science" parameters to the carbon price, see Section 5.4. For the experiment in this Section, we use a one-box approximation of the climate system, assuming that 25% of CO_2 emissions decay very rapidly, and 75% decays at 1 per cent per year. The temperature adjustment process in our experiment formula assumes that 25% of temperature adjustment is reached immediately, while the remaining 75% of the temperature adjustment happens at 1 per cent per year. The two

[22]The damage specification in DICE implicitly assumes ξ, the rate of increase of marginal damages with income, is equal to unity. Here, we extend the DICE damage specification to allow for $\xi \neq 1$.

[23]This transformation would be unnecessary if it was numerically possible to cover all corners of the parameter space. Below, the sensitivity analysis suggests that the current sampling proceduce has sufficient coverage of the parameter space: the estimated parameter contributions to the gap between DICE and the formula remain stable as we include larger subsets of parameters.

[24]The first six have direct counterparts in DICE. For the last two, the growth rates are not constants in DICE; we use the average growth for the first 50 years to obtain the corresponding parameter in the formula.

[25]Illustrating a feature in DICE that is not included in the formula, we note that DICE describes an autonomous decarbonization of the economy and the availability of abatement technologies and their costs.

factors $W(.)$ and $X(.)$ of Section 2.3 become:

$$W(\sigma) = \frac{0.75}{\sigma + 0.01};\ X(\sigma) = 0.25 + \frac{0.0075}{\sigma + 0.01}. \tag{5.34}$$

In the following charts, each dot presents an outcome from one parameter draw.

5.3.2 The choice of the benchmark: climate policy effect

Before testing the formula we should ask if the formula outcome should be tested against the DICE SCC with optimal climate policies or against the DICE SCC in the business-as-usual scenario. The optimal climate policy has an effect on the DICE SCC level – the effect depends on the shape of the damage curve. One may conjecture that a higher order damage exponent, $\psi > 2$, tends to lead to damages that are convex in concentrations, while a smaller exponent imply concave damages. For a convex damage curve, marginal damages are increasing in S. Hence, a cut in emissions results in a reduction in the SCC, so that an active climate policy (a first-best scenario) lowers the SCC as compared to a business-as-usual scenario. Similarly, for $\psi < 2$, one may conjecture that the optimal policy increases the SCC.

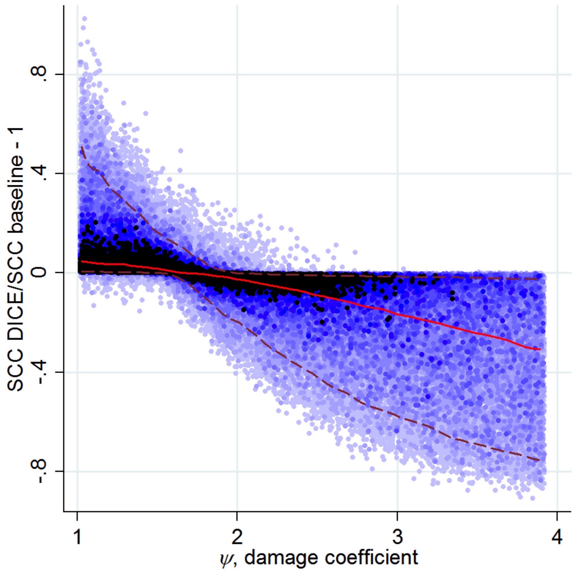
To make an informed choice, we first quantify the above effect of the climate policy on the SCC in DICE. For each parameter draw, we calculate two scenarios. The first scenario assumes a baseline policy without emission reductions. The second scenario is based on optimal policy, implying that abatement options and their development over time also enter the SCC calculations.

Figure 5.1 shows the policy impact on the SCC, calculated as the relative change [SCCpolicy–SCCnopolicy]/SCCnopolicy. The figure confirms that for low values of ψ ($<$ 1.5), climate policy increases the SCC, as damages are a concave function of emissions, and thus lower emissions lead to higher marginal costs. For high values of ψ ($>$ 2), climate policy decreases the equilibrium marginal costs of emissions. For very convex damages ($\psi = 4$), responsive climate policy reduces the marginal costs of emissions on average by 40%. For climate damages that are quadratic in the temperature rise, the equilibrium carbon price is relatively insensitive to policies, with an average decrease of <10% brought by optimal climate mitigation policies. This result is not a surprise: Nordhaus (2008) reports the SCC both under the baseline and optimal policy scenario and finds that optimal policy reduces the SCC by less than 5 percent.

The average change, over the full sample, of the SCC brought by climate policy is 15%.[26] The change is relatively large for SCC values far from the median. With

[26] Let ge = policy/nopolicy be the effect; 0.15 is the average value for |ge–1|.

Figure 5.1: Climate policy effect on the SCC



Efficient climate policies reduce (increase) the SCC for large (low) values of ψ. On the vertical axis, the relative gap in the SCC between the climate policy scenario and the baseline with no policies. Each dot presents one parameter draw. The figure shows also the moving median, p5 and p95 lines. Darker dots present observations overlaying each other. Black dots indicate areas with more than 10 observations per square of 0.012x0.005.

this observation in mind, we note that in spirit our formula is closer to gauging the no-policy SCC than the policy SCC: the formula has no policy variable. We thus use the business-as-usual DICE SCC as our benchmark in the analysis.[27]

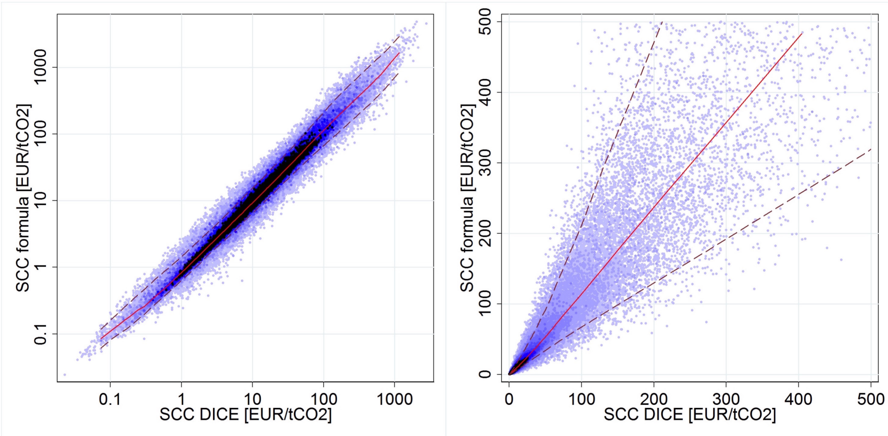
5.3.3 Testing the formula

We look first at the values of the outcome variables, that is, the SCC values predicted by the formula and DICE. In Figure 5.2 (left), we show the full set of outcomes on log-scale. The SCC outcomes are clustered along the 45° line, with a correlation of 0.985: there is a close association between the relative changes of the outcomes. Figure 5.2 shows the center of the distribution (median) as the solid line, and the 5% and 95%

[27]There are also reasons of analysis that rationalize the choice. In particular, to ensure that we cover the entire parameter space, parameter values far from the median are oversampled compared to a more realistic parameter distribution. Hence, the expected difference between policy and no-policy SCCs is smaller than implied by the sampling procedure. As we will see below, for the full range of parameter values, the SCC varies by factor 10,000, from 0.1 to 1000 €/tCO_2, so that the effect of policy is small, compared to the effect of parameter variations. Also, on the relevant domain the interaction of the convex damages and concave temperature adjustment approximately cancel out.

cutoffs of the cumulative distribution as the dashed lines.

Figure 5.2: The DICE and formula SCC



Each dot corresponds to one parameter vector realization with the horizontal and vertical coordinates presenting, respectively, the DICE and our formula SCC values for the year 2015, in 2010 Euros. Left panel: logarithmic scale. Right panel: absolute values, with highest values eliminated for exposition. Both graphs show also the moving median, p5 and p95 lines. Darker dots present observations overlaying each other. Black dots indicate areas with more than 10 observations per square of 0.02x0.02 (left) or more than 100 observations per square of 1x1 (right).

In Figure 5.2 (right), we show the same information for the raw values. For visibility, the figure shows the observations having lower value than 500 €/tCO_2. The correlation between the absolute values of the outcomes is 0.920. The overall takeaway from the two figures is that the formula predicts the absolute level of the DICE SCC with a slight upward bias; the relative changes are closely connected. Moreover, the relative precision (log-scale) does not noticeably change when moving to extreme parameter draws while the absolute prediction error, naturally, depends on the SCC level (absolute scale).

We turn to address the precise sources of the prediction error (the SCC gap), using classical regression analysis. We regress the log difference $[\ln(\text{FormulaSCC}) - \ln(\text{DICESCC})]$on the independent variables (parameters) to assess the contribution of each parameter to the gap. As usual, the log specification facilitates a percentage change (right-hand side variable linear) or elasticity interpretation (right-hand side variable in logs) of the estimated parameters. Specifically, we identify the parameters that explain majority of the variation in the gap by a stepwise inclusion of parameter sets in Table 5.1 below.

The first column reports the eight most important parameters for explaining the gap. They are introduced as linear terms in the regression, so that the reported coefficient gives the main effect of each parameter on the gap.[28] In the analysis, we subtract the mean from the parameter; the coefficients for the linear terms can be interpreted as the marginal effects at the mean value. Thus, for example, one per cent increase in the climate sensitivity leads to 0.26 per cent increase in the gap. The parameters reported in column 1 all enter the formula. The reported eight parameters explain 32 per cent of the variation in the gap ($R^2 = .32$). This is perhaps not surprising since the same parameters explain the majority of the variation also in the DICE outcomes (see Table 5.D.1 in the Appendix for the precise analysis of the explanatory power of the reported eight parameters for the DICE outcomes).

The second column introduces two additional terms: interactions $\psi \times \rho$ and $\psi \times \eta$. We see that the explained gap variation doubles to $R^2 = .64$, while the estimated main effects in the first eight rows remain stable. These two interaction terms have the largest within-sample explanatory power (column 6, to be explained shortly) of all possible 14 linear and 91 interaction terms. This finding is consistent with the conjecture stated after equations (5.20)-(5.22). The interactions are absent in our formula but they are relatively important for the DICE SCC (see Table 5.D.1 in the Appendix). Intuitively, the loss from not having the interactions in the formula is best understood by considering a high value for damage exponent ψ (> 2) combined with a low discount rate ρ. Marginal damages are increasing with temperatures over time; but this is not taken into account by the formula since marginal damages are assumed independent of the temperature levels. Thus, by not including the temperature dependence, the formula understates the damages in the long run which receives a high weight when discount rate ρ is below the mean discount rate (i.e., independent variable "discounting" is negative).[29] For ρ is above the mean value, the formula's overstatement of the shorter-term damages receives more weight, and then the formula overshoots the DICE SCC.

When ψ is low (< 2), damages are concave and the mistake from not including temperature dependence in the formula leads to opposite conclusions: shorter-term damages are understated and the longer-term damages are overstated; discounting dictates which bias is important in the overall determination of the SCC gap. In Appendix 5.E, we provide a more detailed analysis of the parameter draws where the formula either over- or undershoots by factor 2: there is clear evidence that interaction $\psi \times \rho$ contributes strongly to the gap in these worst cases. Finally, most of the variation in the climate discount rate σ in (5.23) comes through the pure discount rate ρ and the elasticity of marginal utility η; the interaction terms $\psi \times \rho$ and $\psi \times \eta$.

[28] As we take the gap in logs, and we know that the dependent variables are about linear in $\ln(c)$ and $\ln(\omega)$, it is natural to transform these two parameters into their logarithms.

[29] The interaction term $\psi \times \rho$ is negative (ψ above average, ρ below average), so the positive coefficient of 9.3 is consistent with the interpretation.

can be similarly interpreted.

The third column adds all remaining linear terms (14-8=6 parameters). This has no practical impact on the results; R^2 and the previously reported effects remain stable. The fourth column adds all the remaining interactions, leading to the full set of parameters used in explaining the gap variation. The R^2 increases to .82. We note that all reported parameter contributions remain stable as we move from left to the right, column by column, excluding the contribution of discounting. The movement of the estimated coefficient for the discount rate is suggestive of relevant interactions between the discount rate and the remaining parameters; however, individually, none of these stand out statistically or quantitatively important in a sense that we discuss next.

To gauge the potential of any given parameter (or interaction) to cause a large SCC gap, we report the spread of the parameter in the sample; that is, the fifth column reports the difference between the max and min values of the parameter (or, interaction) in the support. The final column then reports the gap caused when the parameter (or, interaction) moves from its mean value to its maximal or minimal value, to identify the most important contributions to the gap. This number is calculated as half the parameter spread multiplied with the estimated coefficient. Clearly, interaction $\psi \times \rho$ stands out. For intuition, moving from the mean $\psi \times \rho$ value to the min or max value of the interaction implies an increase of .7 in the gap, which, since the regression expresses the gap in logs, implies a factor two increase in the absolute value of the gap. None of the other reported (or non-reported) effects or interactions come close in quantitative magnitudes. The second-largest contribution comes from interaction $\psi \times \eta$, and the third-largest, but by factor 2 smaller, comes from the climate sensitivity parameter. We thus expect that those cases where the gap between the formula and DICE will exceed a factor 2 will most likely be found in the far corners of $\psi \times \rho$, which is confirmed by Figure 5.E.1 in Appendix 5.E.

With this background on the sensitivity analysis, we conclude the testing of the formula by plotting the raw value of the SCC gap on the level of the DICE SCC in Figure 5.3. It depicts the ratio of the SCCs plotted against the level of the DICE SCC. Over our parameter space, the SCC ranges by a factor 10,000, from 0.1 to 1000€/tCO_2. Throughout this range, in 90% of all observations the formula returns a value between 65% and 174% of the value calculated by DICE, with the average ratio between the two 1.04, and standard deviation of 0.36.[30] The figure shows more details: the tendency of the formula to exceed the DICE value at the high end of the distribution, and to fall short of the DICE value at SCC values close to 1€/tCO_2.

[30]The average of the natural log of the ratio equals –0.01, with standard deviation 0.30 with an overall 5-95% interval [–0.43,0.55].

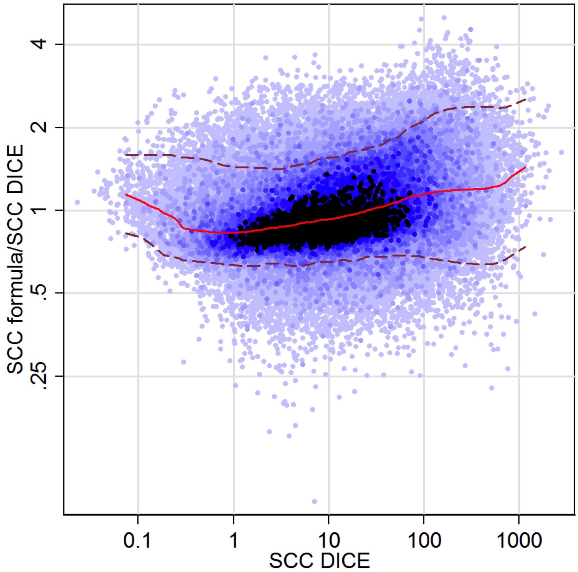
Table 5.1: Relative gap between formula and DICE SCC values: dependence on main parameters

	OLS gap (1)	OLS gap (2)	OLS gap (3)	OLS gap (4)	within-sample spread (5)	corner-center effect (6)
$\ln(c)$	0.255	0.255	0.255	0.225	1.563	0.199
$\ln(\omega)$	0.043	0.044	0.044	0.045	3.219	0.072
ψ	-0.037	-0.037	-0.037	-0.038	2.900	0.055
ξ	0.202	0.202	0.202	0.226	1.263	0.143
ρ	1.733	1.692	1.693	1.093	0.075	0.041
η	-0.100	-0.100	-0.100	-0.103	2.478	0.127
g	-3.793	-3.825	-3.849	-3.313	0.109	0.032
l	10.13	9.894	9.886	10.39	0.005	0.029
$\psi \times \rho$		9.279	9.278	9.803	0.142	0.694
$\psi \times \eta$		0.192	0.192	0.194	4.582	0.446
Other linear vars	NO	NO	YES	YES		
Other interactions	NO	NO	NO	YES		
No. of independent vars	8	10	16	105		
No. of obs.	100,000	100,000	100,000	100,000		
R^2	0.316	0.640	0.642	0.815		

Note: All regressions include a non-reported constant. All reported coefficients are significant at p=0.01; t-values for reported coefficients are 10 or above. The first 4 columns regress the gap between the formula SCC (log) and the DICE SCC (log). Column 5 presents the full spread of the independent variable in the sample (max–min). The last column multiplies the absolute value of the coefficient with the spread, to assess the maximum change in the gap within the sample explained by the independent variable.

Given the above sensitivity analysis, we evaluate that the largest part of the deviations arise from the non-linear relationships between CO_2 concentrations, temperatures, and damages that are not captured by the formula.

Figure 5.3: The ratio of the SCCs



Each dot corresponds to one parameter vector realization with the horizontal and vertical co-ordinates presenting, respectively, the formula-DICE SCC ratio and the DICE SCC values for the year 2015, in 2010 Euros. Both axes have log scale. The figure shows also the moving median, p5 and p95 lines. Darker dots present observations overlaying each other. Black dots indicate areas with more than 10 observations per square of 0.02x0.01.

5.4 Experiment II: carbon price distribution

Our second experiment builds on the extended version of the formula that allows for a more flexible description of the climate system (Proposition 5.2 in Section 5.2.3). We conduct a Monte Carlo experiment as in Section 5.3; that is, we take 100,000 draws for the parameters entering the formula using right-skewed log-normal distributions.[31] In addition, in contrast with the experiment in Section 3 where the climate system was fixed, here we also sample the climate system parameters. The overall objective of this second experiment to generate, from the underlying parameter distributions, a carbon price distribution that is comparable to the distribution of outcomes from the IAMs in the literature. Since our representation of the SCC distribution builds on a closed-form formula, it allows us to provide a breakdown of how different sets of parameters such as those related to the climate system or damages contribute to the

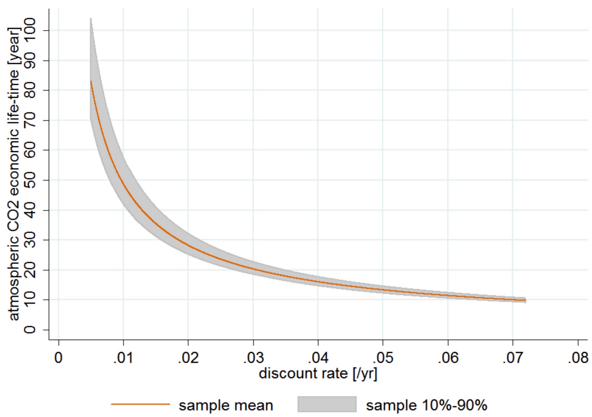
[31] Recall that in Section 5.3, for the purpose of testing the formula, we translated the log-normals to log-uniforms. Here, since the testing is not the focus, we use the original log-normal distributions for the draws.

SCC distribution.

We start by introducing the sampling of the climate system parameters. Recall from Section 5.2.3 that carbon cycle parameters enter the formula through term $W(\sigma, \mathbf{a}, \delta_S)$ that measures the economic life-time of emissions; the temperature adjustment enters through the term $X(\sigma, \mathbf{b}, \varepsilon)$. We use 16 different models for the carbon cycle from Joos et al. (2013), and 20 different models for the temperature adjustments from Caldeira and Myhrvold (2013); see Appendix 5.C. In the experiment, we randomly select one of the 16 carbon cycle models and one of the 20 temperature adjustment models. This defines a draw for the climate system.

Figure 5.4 presents the economic life-time of CO_2, $W(\sigma, \mathbf{a}, \delta_S)$, as a function of the discount rate, for the ensemble of carbon cycles in Joos et al. (2013) that we use in the analysis. The figure shows the mean and the full support of $W(.)$ for a given discount rate. We see that for a discount rate of 3% per year, the economic life-time is approximately 20 years. For a discount rate of 1%, the economic life-time increases to 50 years. The variation between carbon cycles is small compared to the variation caused by the moving discount rate. Thus, Figure 5.4 suggests a limited economic meaning for the variation between carbon cycles.

Figure 5.4: Economic life-time $W(\sigma, \mathbf{a}, \delta_S)$ of atmospheric CO_2 as a function of the discount rate

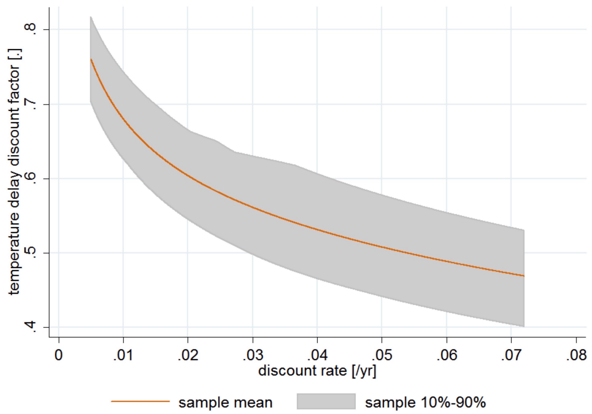


Based on 16 models provided in Appendix 5.C.

Similarly, Figure 5.5 presents the discount factor $X(.)$ associated with the slow temperature adjustment and the ensemble of temperature adjustment models from Caldeira and Myhrvold (2013). For a discount rate of 3% per year, the discount factor is between .45 and .58. For a discount rate of 1% per year, the discount factor is between .68 and .8. Hence, omitting the temperature delay, as in Golosov et al. (2014), easily biases the carbon price by factor 2. This point has been elaborated also in Gerlagh and Liski (2012). The figure also shows that the variation between temperature delay models is more important, in economic terms, though the effect of changing the discount rate is still substantially larger.

Combining the two factors $W(.)$ and $X(.)$, we see that a drop in the discount rate from 3%/yr to 1%/yr increases the factor WX from about 10 to about 40: a 2%/yr decrease in the discount rate increases the net present value of future damages by about 4.

Figure 5.5: Discount factor $X(\sigma, \mathbf{b}, \boldsymbol{\varepsilon})$ for the net present value of damages because of the delay in temperature adjustment.



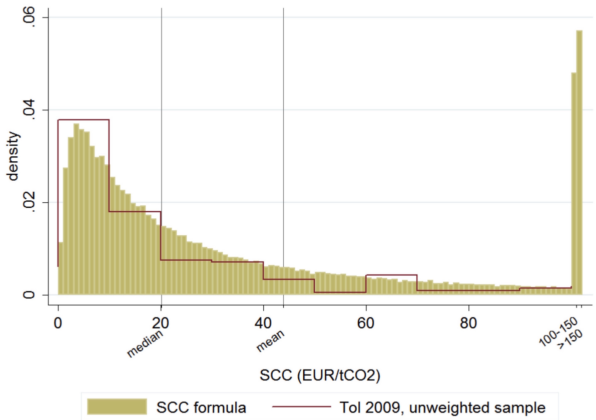
Based on 20 models provided in Appendix 5.C.

Figure 5.6 depicts the density distribution of the SCC, obtained by sampling all parameters, as explained. The resulting distribution is strongly right-skewed with a median SCC of 20€/tCO_2, mean 44€/tCO_2, and more than 10 percent probability for a SCC higher than 100€/tCO_2. A distribution from IAM outputs of 232 distinct studies results in a similar distribution when the numbers are converted to comparable units Tol (2009).

It is not straightforward to develop a statistical test for the goodness of the match with the distribution from the literature, given the elusive nature of this "data". We take it as given that Figure 5.6 is suggestive of consistency with the wider literature, and now we identify the determinants of the properties of the SCC distribution.

We want to identify measures for the first and second moments of the SCC distribution. We define a skewness measure (SM), equal to the relative gap between the expected or mean value $E[.]$ and the median value $M[.]$. For a log-normally dis-

Figure 5.6: Density distribution of the SCC



Values are reported for the year 2015, in 2010 Euros. Tol's distribution comes from the database that supports his paper (Tol, 2009). SCC values in Tol (2009) were divided by 3.67 to convert 1995\$/tC into 2010€/tCO_2, and then increased by 3% for each year between publication and 2015 to correct for the trend. Further information on the parameters' distributions is provided in Appendix 5.C.

tributed variable, it is given by

$$SM[X] = \frac{E[X]}{M[X]} - 1 = e^{-\frac{1}{2}\vartheta^2} - 1, \tag{5.35}$$

where $\vartheta = sd[\ln X]$ is the standard deviation of the underlying normal variable. Since a greater spread in an underlying variable translates into a greater standard deviation, the value of $SM[.]$ is the increase in the expected value, relative to the median. It follows from the definition of the skewness measure and its formula for a lognormal distribution that, if the factors composing the SCC are lognormal distributed, then the SCC is lognormal distributed, and the SM for the SCC can be decomposed into the SM of its parts:

$$Z = Z_1 \cdot Z_2 \text{ and } Z_1, Z_2 \sim \text{lognormal} \Rightarrow \tag{5.36}$$

$$1 + SM[Z] = (1 + SM[Z_1])(1 + SM[Z_2]). \tag{5.37}$$

The numbers in Table 5.2 provide some initial insight in the contribution of the SCC's parts to the gap between mean and median SCC. The table shows that the carbon cycle and temperature adjustment speed uncertainty have a low skewness measure.

But climate sensitivity, damages, and discounting each individually introduce considerable spread and right-skewedness to the SCC distribution. Furthermore, the table shows that, indeed, the skewness measure for the SCC is approximately equal to the (multiplicative) cumulative of its parts:

$$SM\left[SCC\right] \approx \left(1 + SM\left[W\right]\right)\left(1 + SM\left[X\right]\right)\left(1 + SM\left[c^2\right]\right) \\ \times \left(1 + SM\left[\omega\right]\right)\left(1 + SM\left[WX\right]\right) - 1, \quad (5.38)$$

where $SM[W]$, $SM[W]$, and $SM[WX]$ denote the skewness measures of $W(.)$, $X(.)$, and $W(.)X(.)$, associated with the carbon cycle parameters, temperature adjustment parameters, and climate discount rate, respectively.

Table 5.2: Sources of SCC variation and skewness measures

Sources of variation	Median €/tCO_2	Mean €/tCO_2	Standard deviation €/tCO_2	Skewness measure
None	29.5	29.5	0	0%
Carbon cycle	31.3	32.8	3.2	5%
Temperature adjustment	19.5	18.6	1.7	-5%
Climate sensitivity	29.6	38.9	30.4	31%
Damage	29.3	39.3	31.8	34%
Discount rate	29.5	34.1	18.9	16%
All	20.2	43.9	75.5	117%

Each row presents results from the Monte Carlo experiment, where only the first column parameters are varied. For the carbon cycle and temperature adjustment we estimated a median cycle (see Tables 5.C.2 and 5.C.3)

The joint interaction of all uncertainties leads to a distribution where, as shown in Figure 5.6, the mean is twice as large as the median. The result is consistent with previous studies on the sensitivity (Hope, 2008; Nordhaus, 2008; Newbold et al., 2013), but importantly, the formula helps to identify how the uncertainties for these parameters add up in shaping the SCC distribution. A 1% increase in the skewness measure for the damage parameter translates into approximately a one percent increase in the SCC SM. Similarly a 1% increase in the climate sensitivity SM translates into approximately a 2% increase in the skewness measure of the SCC.

The formula also allows us to assess the sensitivity of the distribution to the annual discount rate as part of the distribution analysis (Table 5.3). The mean and median SCC increase by half when the discount rate, σ, falls from 3% to 2%, increase by factor 2 when the discount rate falls from 2% to 1%, but they increase more than eight-fold when σ falls from 1% to 0.1%. Due to the non-depreciating climate boxes, some climate impacts are permanent, fattening the tail of the SCC distribution when discounting falls towards zero. For a discount rate converging to zero, the expected SCC is without bound. This effect cannot be captured by analytical formulas having only one climate box.

Table 5.3: Discount rate sensitivity of the SCC

Discount rate	Median €/tCO_2	Mean €/tCO_2	Standard deviation €/tCO_2
0.1%	280	511	698
1%	35.7	63.4	83.8
2%	18.3	32.6	43.0
3%	12.3	21.9	28.9

Note: Each row presents outcomes from the Monte Carlo experiment, where only the discount rate is fixed.

5.5 Conclusion

This study offers a relatively simple, closed-form, formula for determining the SCC. We have derived the formula under a specific set of assumptions regarding economic growth, population growth and savings to provide an approximation of richer climate-economy descriptions. The formula is tested by comparison with a mainstream IAM.

In this exercise, draws are taken from parameter distributions for the key variables, of which some also enter the formula. A comparison then reveals that, despite its low informational requirement, the formula explains the parameter-driven variation of the SCC in DICE, the IAM used for the comparison. An application of the formula shows that for a parameter distribution, the formula generates a SCC distribution that comes close to that obtained in a comprehensive survey of previous SCC estimates.

The approach has limitations: it does not present an analysis of policy making under uncertainty. However, the results are quite informative about the basic mechanisms of SCC determination in deterministic IAMs. First, they imply that the SCC, as presented by the benchmark IAMs, is relatively independent of current or future policy choices and abatement options. The analytics demonstrates that only a few mechanisms are needed to understand the core of the determination of the SCC, as described by the mainstream IAMs.

Second, the analytic structure allows assessment of how different parameter sets contribute to the SCC value. Based on primitive parameter distributions, we found a strongly right-skewed SCC distribution, with a median of 20€/tCO_2, mean

44€/tCO_2, and a 10% probability of the SCC exceeding 100€/tCO_2. The median (or best-guess) value for the SCC can readily be calculated using rule-of thumb values for the main parameters; however, the mean SCC is the more relevant measure for policymaking. Spread regarding the appropriate discount rate, climate sensitivity and damages mostly contributed to skew in the SCC distribution. The formula can easily be exploited to understand the effects of subjective choices on the deterministic SCC outcomes. In particular, the climate-system description with some fraction of carbon slowly depreciating, explains the effect of the discount rate: a reduction in the effective discount rate from 2% to 1% approximately doubles the SCC outcome, while the SCC increases more than 8-fold if this discount rate is reduced from 1% to 0.1%.

Finally, the formula indicates, and as has been noted in the literature, that the trajectory of the SCC is expected to increase approximately with income levels, as the size of the economy determines what is at stake. Yet, the scope of the current formula for such analysis is restricted since it excludes within-model parameter uncertainty (see Gerlagh and Liski (2014), for analytical steps in this direction).

From a science-policy perspective, the formula answers to a call for a better connection between research in the climate-economics domain and the users of that knowledge (Gerlagh and Sterner, 2013). Without ignoring the insights gained in recent years on fat tails for damages, climate tipping points, and policy under uncertainty, much of the basic understanding about the cost-benefit analysis of climate policy is still close to the insights of the early 1990s. The formula captures some of these insights, enabling the stakeholders to reflect on the methods used to derive the SCC. By doing so, it can facilitate the communication between stakeholders and the research community.

Appendix 5

5.A The optimal control problem (5.1)-(5.4)

The current-value Hamiltonian for (5.1)-(5.4) reads

$$\mathcal{H} = LU\left(\frac{C}{L}\right) + p\left[F\left(K,E,T;t\right) - \delta_K K - C\right] - \tau\left[E - \delta_S S\right] - \chi\left[\varepsilon\left(\varphi\left(S\right) - T\right)\right]. \tag{5.A.1}$$

Since we defined τ and χ to measure the negative value of the stock of atmospheric CO_2 and global temperature change, respectively, the first order conditions are

$$\frac{\partial\mathcal{H}}{\partial C} = 0, \tag{5.A.2}$$

$$\frac{\partial\mathcal{H}}{\partial E} = 0, \tag{5.A.3}$$

$$\dot{p} = \rho p - \frac{\partial\mathcal{H}}{\partial K}, \tag{5.A.4}$$

$$\dot{\tau} = \rho\tau + \frac{\partial\mathcal{H}}{\partial S}, \tag{5.A.5}$$

$$\dot{\chi} = \rho\chi + \frac{\partial\mathcal{H}}{\partial T}. \tag{5.A.6}$$

After substituting the functional forms, we derive the FOCs (5.5)-(5.9). The FOCs (5.8) and (5.9), we can rewrite as

$$\tau(t) = \varepsilon\int_t^\infty e^{-(\rho+\delta_S)(s-t)}\chi(s)\frac{\partial\varphi}{\partial S}(s)ds, \tag{5.A.7}$$

$$\chi(t) = -\int_t^\infty e^{-(\rho+\varepsilon)(s-t)}p(s)\frac{\partial F}{\partial T}(s)ds. \tag{5.A.8}$$

In order to express the social costs of carbon as the net present value of marginal damages, we use (5.7) and identities (5.12), (5.13), (5.14), to connect the price deflator $R(.)$ to the marginal utility measure p

$$\frac{\dot{R}}{R} = \frac{\dot{p}}{p} - \rho \Rightarrow R(s) = \text{cnst}\cdot e^{-\rho s}p(s) \Rightarrow \tag{5.A.9}$$

$$R(s,t) = e^{-\rho(s-t)}\frac{p(s)}{p(t)}. \tag{5.A.10}$$

We can now rewrite (5.A.7) and (5.A.8) as

$$\tau(t) = \varepsilon p(t) \int_t^\infty e^{-\delta_S(s-t)} R(s;t) \frac{\chi(s)}{p(s)} \frac{\partial \varphi}{\partial S}(s) ds, \tag{5.A.11}$$

$$\chi(t) = -p(t) \int_t^\infty e^{-\varepsilon(s-t)} R(s;t) \frac{\partial F}{\partial T}(s) ds. \tag{5.A.12}$$

Substitution of $t = 0$ in the first equation, substituting t for s, and substituting $R(t,0) = R(t)$, and $SCC(t) = \tau(t)/p(t)$, gives (5.16).

5.B Parameters for the Monte Carlo experiment comparing the extended DICE model with the formula

We included 12 major parameters from DICE Nordhaus (2008) in our Monte Carlo parameter sample, and add the damage temperature elasticity and damage income elasticity. These parameters are listed in the table below. For each parameter, we derived distributions from the literature as stated in the last column of the table below. The central values are more or less in line with the typical values used for DICE, apart from the elasticity of marginal utility. Compared to the parameters listed for the sensitivity assessment for DICE (Table VII-1), we included the pure rate of time preference, the elasticity of marginal utility, the decline rate of labor productivity growth and decarbonization, and short- to long-term backstop costs. We excluded the fossil fuel resources and a transfer coefficient in the climate module. For consistency between the parameters and initial values, we recalibrated the DICE model with respect to the initial capital stock, productivity, population size and growth in the first decade 2005-2015.

The literature on climate damages deals with damages for a given temperature increase. To match distributions as suggested by this literature, we jointly estimate the damage parameter and damage temperature power coefficient as follows. We rewrite (5.18), normalizing ω as a measure for damages at 3 Kelvin temperature perturbation:

$$F(K, E, T; t) = Y(K, E; t) \left[1 - \omega \left(\frac{T}{3} \right)^{\Psi} \left(\frac{Y(K, E; t)}{L\bar{y}} \right)^{\xi - 1} \right]. \tag{5.B.1}$$

Using this formulation, we draw ω and ψ independently, and (5.31) becomes

$$SCC = \omega \frac{1.3c^2}{9m} W(\sigma, \mathbf{a}, \delta_S) X(\sigma, \mathbf{b}, \varepsilon) \left(\frac{Y}{L\bar{y}} \right)^{\xi - 1} Y. \tag{5.B.2}$$

Table 5.B.1: DICE parameter distributions

Parameter [Units]	Median	Lower cutoff value*	Upper cutoff value*	Source
Climate sensitivity [Kelvin]	3	1.3719	6.5601	(a)
Damages at 3 Kelvin (relative to output)	0.027	0.0054	0.135	(b)
Damage temperature power coefficient	2	1	4	
Damage income elasticity	1.15	0.67	2	(i)
Pure rate of time preference [yr^{-1}]	0.02	0.005	0.08	(c)
Elasticity of marginal utility	1.2	0.5	3	
Asymptotic size of population [mn]	10,000	7,300	13,699	(d)
Productivity growth [dec^{-1}]	0.154	0.109	0.218	(e, f)
Decline rate of productivity growth [dec^{-1}]	0.001	0.0005	0.002	(g)
Decarbonization rate [dec^{-1}]	0.073	0.0479	0.1113	(e, g, h)
Decline rate of decarbonization [dec^{-1}]	0.003	0.0013	0.007	(e, g, h)
Backstop price [USD/tC]	1,170	768	1783	(g, h)
Ratio initial to final backstop price	2	1.3122	3.0482	(g, h)
Decline rate of backstop price [dec^{-1}]	0.05	0.0275	0.0909	(g, h)

Parameter distributions are log-normal, truncated at 2 standard deviations from the median; *For truncated distribution. Sources: (a) Dietz and Asheim (2012); (b) Tol (2009); Gerlagh and Liski (2012); (c) Weitzman (2001); (d) UN (2011); (e) World World Bank (2012); (f) OECD (2012); (g) Nordhaus (2008); (h) IPCC (2007) (i) Hoel and Sterner (2007).

5.C Parameters for the Monte Carlo experiment using the SCC formula

For the second experiment, we vary the parameters c, ω and σ, and use 16 alternative carbon cycle representations and 20 temperature adjustment models (see Tables 5.C.1 and 5.C.2) to calculate the SCC according to equation (5.30). The parameter Y in the formula is fixed at 66.2 trillion Euros. The parameters c, ω and σ are drawn from a lognormal distribution as specified in Table 5.B.1. The lognormal distributions are based on the literature as noted in the last column of Table 5.B.1, and chosen to reflect the fact that the dispersion regarding the appropriate parameter values is highly asymmetric, with greater dispersion for high values. Still, some very high (or low) values are deemed unrealistic. The latter is captured by our use of cutoffs.

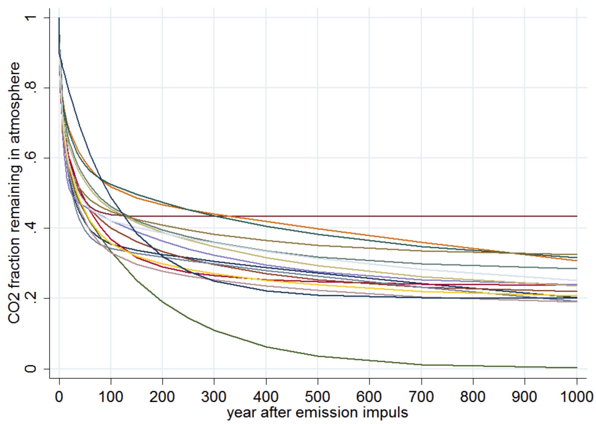
We generated a Monte Carlo parameter set and derived the SCC using Stata; the full source code is available online through http://www.sciencedirect.com/science/article/pii/S0095069616000061.

Table 5.C.1: SCC parameter distributions

Parameter [Units]	Median	Mean*	Standard deviation*	Lower cutoff value*	Upper cutoff value*	Source
Climate sensitivity [Kelvin]	3	3.218	1.222	1.3719	6.5601	(a)
Damages parameter	0.003	0.004	0.0032	0.0006	0.015	(b)
Climate discount rate	0.018	0.2224	0.0154	0.005	0.072	

Parameter distributions are log-normal, truncated at 2 standard deviations from the median; *For truncated distribution. Sources: (a) IPCC (2007); (b) Tol (2009); Gerlagh and Liski (2012).

Figure 5.C.1: Airborne fraction of CO_2 emissions for 16 models,



Based on 16 models provided in Table 5.C.2.

Table 5.C.2: Carbon cycle parameters

Model	a_0	a_1	a_2	a_3	δ_{S_1}	δ_{S_2}	δ_{S_3}
NCAR_CSM1.4	0	0.367	0.354	0.279	0.0006	0.0353	0.1881
HadGEM2-ES	0.434	0.197	0.189	0.18	0.0433	0.0433	0.255
MPI-ESM	0	0.586	0.183	0.231	0.0056	0.1106	0.1112
Bern3D-LPJ	0	0.515	0.263	0.222	0.0005	0.0218	0.2583
Bern3D-LPJ	0.28	0.238	0.238	0.244	0.0036	0.0260	0.2029
Bern2.5D-LPJ	0.236	0.099	0.385	0.28	0.0043	0.0171	0.3865
CLIMBER2-LPJ	0.232	0.276	0.49	0.003	0.0037	0.1494	0.1494
DCESS	0.216	0.291	0.241	0.252	0.0026	0.0275	0.2943
GENIE	0.215	0.249	0.192	0.344	0.0037	0.0254	0.2323
LOVECLIM	0	0.361	0.45	0.189	0.0006	0.0461	0.4384
MESMO	0.285	0.294	0.238	0.183	0.0022	0.0400	0.4965
UVic2.9	0.319	0.175	0.192	0.315	0.0033	0.0377	0.2632
ACC2	0.178	0.165	0.38	0.277	0.0026	0.0271	0.2686
Bern-SAR	0.199	0.176	0.345	0.279	0.0030	0.0252	0.2433
MAGICC6	0.205	0.253	0.332	0.21	0.0017	0.0455	0.3339
TOTEM2	0	0.203	0.7	0.097	0.00001	0.0089	63.2911
Median	0.22	0.279	0.278	0.222	0.0035	0.0507	0.2892

Parameters taken from Joos et al. (2013), $\eta_0 = 0$ for all models. The median cycle has been determined based on the 16 individual models.

Table 5.C.3: Temperature adjustment parameters

Model	b_0	b_1	b_2	ε_0	ε_1	ε_2
BCC-CSM1.1	0.235	0.352	0.412	1.447	0.162	0.007
BCC-CSM1.1(m)	0.303	0.334	0.363	1.678	0.116	0.008
CanESM2	0.458	0.245	0.298	0.469	0.037	0.003
CSIRO-Mk3.6.0	0.197	0.212	0.591	1.248	0.113	0.005
FGOALS-g2	0.333	0.227	0.440	0.621	0.036	0.003
FGOALS-s2	0.079	0.453	0.468	5.155	0.212	0.003
GFDL-CM3	0.181	0.284	0.535	1.342	0.139	0.005
GFDL-ESM2G	0.130	0.432	0.438	3.390	0.315	0.003
GFDL-ESM2M	0.160	0.385	0.455	2.688	0.242	0.004
INM-CM4	0.197	0.481	0.322	3.106	0.188	0.002
IPSL-CM5A-LR	0.216	0.394	0.390		0.062	0.002
IPSL-CM5A-MR	0.185	0.379	0.436	2.262	0.097	0.003
IPSL-CM5B-LR	0.292	0.316	0.393	2.075	0.114	0.006
MIROC5	0.259	0.384	0.356	1.565	0.212	0.004
MIROC-ESM	0.204	0.364	0.432	1.449	0.107	0.003
MPI-ESM-LR	0.278	0.315	0.407	1.106	0.149	0.006
MPI-ESM-MR	0.230	0.380	0.390	2.463	0.172	0.006
MPI-ESM-P	0.302	0.317	0.380	1.733	0.141	0.006
MRI-CGCM3	0.305	0.356	0.339	1.473	0.095	0.006
NorESM1-M	0.223	0.297	0.480	1.942	0.145	0.005
Median	0.222	0.331	0.448	0.979	0.198	0.004

Parameters taken from Caldeira and Myhrvold (2013). The median cycle has been determined based on the 20 individual models.

5.D Explaining the DICE outcome using regression analysis

The sensitivity analysis looks at the gap ln(formulaSCC/DICESCC). We can also regress the ln(formulaSCC) and ln(DICESCC) separately on the same right hand side variables; the results in text can also be obtained by merging the results of these two separate regressions. However, it is of some interest to see how the central parameters explain the levels; we present the results for DICE in the table below. We present in the table below all parameters that have a max within-sample effect of at least 2, meaning that their variation can cause a factor 2 change in the DICE SCC.

Column 1 shows that the eight most important parameters explain more than 90% of the variation; the parameters are the same as in the main text. The most important interaction terms (column 2) include those in the text but also one additional interaction.

Table 5.D.1: DICE SCC value dependence on main parameters

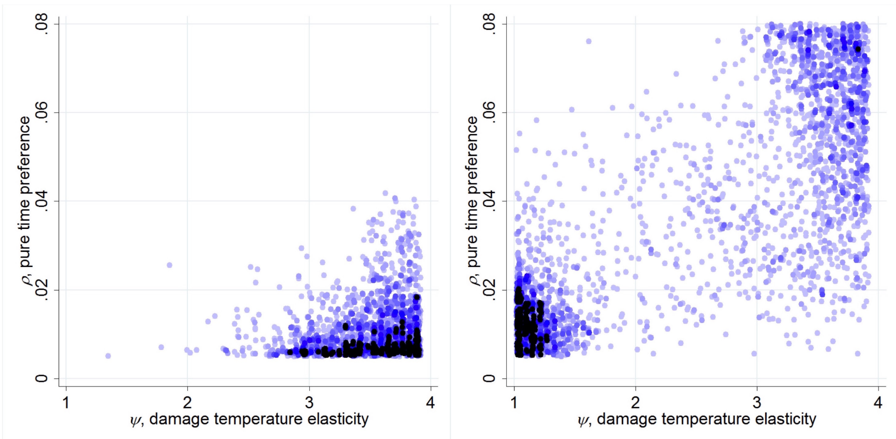
	OLS gap (1)	OLS gap (2)	OLS gap (3)	OLS gap (4)	within-sample spread (5)	corner-center effect (6)
$\ln(c)$	1.89	1.889	1.889	1.888	1.563	4.37
$\ln(\omega)$	0.947	0.947	0.947	0.946	3.219	4.58
ψ	0.0389	0.0385	0.0385	0.0393	2.900	1.06
ξ	0.585	0.661	0.661	0.689	1.263	1.55
ρ	-38.96	-39.95	-39.95	-40.51	0.075	4.57
η	-0.837	-0.838	-0.838	-0.854	2.478	2.88
g	4.57	6.6	6.612	7.585	0.109	1.08
l	47.28	49.21	49.22	49.45	0.005	1.15
$\ln(c) \times \psi$		0.797	0.797	0.796	2.718	2.95
$\psi \times \rho$		-9.135	-9.134	-9.643	0.142	1.98
$\psi \times \eta$		-0.188	-0.188	-0.192	4.582	1.55
Other linear vars	NO	NO	YES	YES		
Other interactions	NO	NO	NO	YES		
No. of independent vars	7	9	16	105		
No. of obs.	100,000	100,000	100,000	100,000		
R^2	0.918	0.977	0.977	0.983		

Note: All regressions include a non-reported constant. All reported coefficients are significant at $p = 0.01$. First 4 columns regress the DICE SCC (log). Column 5 presents the full spread of the independent variable in the sample (max–min). The last column multiplies the absolute value of the coefficient with half the spread, and then takes the exponent, to assess the change in the SCC when moving from the center of the parameter space to the furthest corner for that parameter.

5.E Sensitivity analysis: the parameters associated with extreme deviations

The sensitivity analysis in the text shows that interactions $\psi \times \rho$ and $\psi \times \eta$ are important explanatory variables for the gap between the formula and DICE outcomes. We complement the regression analysis here by collecting all realizations where the formula deviates from the DICE value by more than factor two. In Figure 5.E.1 below all observations where the formula presents less than half the DICE value are characterized by high ψ and low ρ (left panel). Observations where the formula more than doubles the DICE SCC are characterized by either high ψ and high ρ, or low ψ and low ρ. There is no other pair of parameters with such clear patterns. The interaction effect of the next most-important interaction, ψ and η, is too small to see a comparable pattern as below.

Figure 5.E.1: Projections of all formula vs DICE outliers.



Projections of all 1081 observations with $SCCformula < 0.5 \times SCCDICE$ (left panel) and all 2280 observations with $SCCformula > 2 \times SCCDICE$ (right panel), on 2-parameter plane: ψ and ρ. Each dot corresponds to one parameter vector realization. Darker dots present observations overlaying each other.

Chapter 6

Fiscal policy and CO_2 emissions of new passenger cars in the EU

Abstract

To what extent have national fiscal policies contributed to the decarbonisation of newly sold passenger cars? We construct a simple model that generates predictions regarding the effect of fiscal policies on average CO_2 emissions of new cars, and then test the model empirically. Our empirical strategy combines a diverse series of data. First, we use a large database of vehicle-specific taxes in 15 EU countries over 2001-2010 to construct a measure for the vehicle registration and annual road tax levels, and separately, for the CO_2-sensitivity of these taxes. We find that for many countries the fiscal policies have become more sensitive to CO_2 emissions of new cars. We then use these constructed measures to estimate the effect of fiscal policies on the CO_2 emissions of the new car fleet. The increased CO_2-sensitivity of *registration* taxes have reduced the CO_2 emission intensity of the average new car by 1.3 percent, partly through an induced increase of the share of diesel-fuelled cars by 6.5 percentage points. Higher *fuel* taxes lead to the purchase of more fuel-efficient cars, but higher diesel fuel taxes also decrease the share of (more fuel-efficient) diesel cars; the higher *annual road taxes* have no or an adverse effect.

This chapter is based on joint work with Reyer Gerlagh, Thomas Michielsen and Hans Nijland.

6.1 Introduction

Transport accounts for about 23% of energy-related CO_2 emissions (Sims et al., 2014), and 15% of global greenhouse gas emissions (Blanco et al., 2014). Within the EU, passenger cars represent about 12% of EU CO_2 emissions.[1] In 1995, the European Commission launched a strategy to reduce carbon dioxide emission intensity (i.e. emissions per kilometer) for new cars sold in the European Union. Since then, the emission intensity of new sold cars has come down remarkably, especially since 2007.[2] In 2011, the strategy was updated with a proposal to reduce EU transport greenhouse gas emissions by 60%, by 2050 as compared to 1990 levels (European European Commission, 2011b).

The strategy is based on three pillars. The first pillar targets car manufacturers, requiring them to reduce the average emissions of new cars. The associated directive, established in 2009, aims to decrease the average emissions of new sold cars to 130 gCO_2/km by 2015, and 95 gCO_2/km by 2020 (European Parliament, Council of the European Union , 2009).[3] The second pillar aims to ensure that the fuel efficiency information of new passenger cars offered for sale or lease in the EU is made available to consumers to facilitate an informed choice. Labelling is the major instrument to provide information on fuel consumption and CO_2 emissions of cars. Directive 1999/94/EC obliges Member States to provide this information and to transpose the directive into national laws by 18.1.2001 at the latest (European Parliament, Council of the European Union , 1999).

The third pillar aims to influence consumer's vehicle purchase choices by increasing taxes on fuel-inefficient cars relative to fuel-efficient cars. The three pillars are expected to reinforce each other. Increasing the tax burden on fuel-intensive cars, relative to the burden on fuel-efficient cars (third pillar), and providing information (second pillar) is expected to increase the sale of fuel-efficient cars, which in turn makes it more profitable for car manufacturers to produce fuel-efficient cars (the first pillar).

Over the past years, many EU-countries implemented the third strategy pillar, by greening the car taxes through either a revision of purchase taxes, company car taxes or annual road taxes. Contrary to the first and second pillar policies, car taxes, as all other taxes, are decided on a national level, and as a consequence differ across countries. In 2005, the European Commission proposed to harmonise national vehi-

[1] See European Commission (2016)

[2] See Figures 6.1 and 6.2 in the data description. The anticipation of regulation EC/443/2009 (European Parliament, Council of the European Union , 2009) is a possible explanation for the downward trend after 2007.

[3] All data on CO_2 emission/km in this study are determined according to the NEDC guidelines (New European Driving Cycle, the prescribed European test cycle).

cle registration and annual road taxes (European European Commission, 2005), but the proposal was rejected by the member states.

Also the level of, as well as the decline in, the emission intensity of newly purchased cars greatly varies across the European countries. Take for instance petrol cars. In 2010, average emissions from new cars ranged from 130 gCO_2/km (Portugal) to 160 (Luxembourg). Over the period 2001-2010, the emission intensity of petrol cars fell by on average 12% across the EU15. CO_2 emissions of new cars have declined most rapidly in Sweden and Denmark. There are various possible explanations for these different experiences across countries. For example, the fall in Sweden's emission intensity may be attributed to domestic policies (Huse and Lucinda, 2014), or to convergence to the EU average, whereas Denmark's move from being average to becoming one of the most fuel-efficient countries might be the consequence of its aggressive car tax policies.

In this paper, we exploit the variation in the stringency vehicle fiscal policies across countries and time to address the following research question: to what extent have national fiscal policies contributed to the decarbonisation of newly sold passenger cars? We construct a simple model of a representative agent to generate predictions regarding the effect of fiscal policies on average CO_2 emissions of new cars. We study changes at the aggregate level and are interested in differences between countries and changes over time within countries.[4] After presenting the model, we build a dataset in which we compare vehicle tax systems across 15 countries over the years 2001-2010. We use a dataset of vehicle-specific taxes, and use these data to characterize each country's tax system at year t. More specifically, we construct measures for the level and CO_2-sensitivity of car taxes so that we can compare different tax regimes over countries and years. We differentiate taxes by petrol and diesel, so that we construct 8 variables to provide an elaborate characterization of a country's vehicle tax system for a given year. Both the construction of the multiple tax proxies and the multi-country sample mark important contributions to the empirical literature, which typically has considered a single-country single-event.[5]

The constructed variables are used to empirically study the effect of the fiscal treatment, especially the car purchase tax, on the fuel efficiency of newly sold cars. We identify the effect by considering dynamic differences between countries in car taxes and in emission intensities. We control for static differences between countries through country fixed effects, control for income and for common dynamic patters (e.g. EU policies) through time fixed effects. We can identify the effect of fiscal

[4]That is, the model and our econometric analysis do not provide a detailed micro foundation of consumers' decisions; see Berry et al. (1995) or Van Meerkerk et al. (2014) for such an analysis.

[5]See for instance Hennessy and Tol (2011); Huse and Lucinda (2014); Ciccone (2015); d'Haultfoeuille et al. (2014); Chugh and Cropper (2014).

policies on car sales as some countries have consistent low purchase taxes (<30% of car prices) that are not very sensitive to CO_2 emissions (Belgium, France, Germany, Italy, Luxembourg, Sweden, United Kingdom), while Spain has low purchase taxes but these have become substantially more CO_2-sensitive over the period 2001-2010. Greece has high purchase taxes (>30%) but these became less CO_2-sensitive over the years, and the remaining countries (Austria, Denmark, Finland, Ireland, Netherlands, Portugal) have relatively high purchase taxes (>30%), with a CO_2 component that substantially increased over the years (>10 €/(gCO_2/km)), though the countries differ substantially. Our empirical strategy is based on the correlation between the uneven developments in taxes and patterns in the emission intensities for these countries.

Our research has three characteristics, which, combined, make it unique and add to existing literature: first, unlike most studies, our study deals with the effects of car taxes in multiple countries, thus controlling for year-specific effects. This makes it easier to generalize our results. Second, unlike most studies, our study jointly considers three different types of car-related taxes, i.e. registration taxes, road taxes and fuel taxes. This allows for a better insight in the effect of different components of car-related taxes. Third, we provide a method to decompose registration taxes in two parts: the first part measures the level while the second part measures the CO_2-sensitivity. The decomposition allows for a richer analysis.

We find empirical evidence that fiscal vehicle policies significantly affect emission intensities of new bought cars. We find evidence that especially the CO_2-sensitivity of registration taxes and the level of the fuel taxes are important determinants of the emission intensity of new cars. The diesel-petrol substitution induced by changes in the relative taxes for diesel versus petrol cars is an important factor for the average fleet's fuel efficiency. We also find higher CO_2 intensities with increasing income and a clear convergence pattern between EU countries.

6.2 Literature

There is an emerging empirical literature on the effects of fiscal policies on the fuel efficiency of newly sold cars. The general finding is that fiscal policies are an effective tool to influence car purchase decisions. In addition, the literature establishes that purchase taxes are more effective than annual (road) taxes, and that tax reform can cause sizeable petrol-diesel substitution.

A strong example of the responsiveness of car purchases to fiscal policies is provided by d'Haultfoeuille et al. (2014). They assess the effect of the "feebate" system that existed in France in 2008 and 2009. In this system, owners of fuel-efficient cars could receive a tax rebate whereas fuel-inefficient car owners had to pay a fee. The precise rebate and fee thresholds showed up remarkably in the sales for different car types, with large sales increases just below and drops just above the thresholds.

The effectiveness of car taxes can depend on the subtle features of the policy adopted. For example, compared to annual taxes, vehicle acquisition taxes are more effective in directing consumers' buying decisions (Brand et al. 2013; Gallagher and Muehlegger 2011; Klier and Linn 2015; Van Meerkerk et al., 2014). Consumer myopia is considered the main reason for this discrepancy.[6] For fuel costs the evidence is mixed. Where Busse et al. (2013) and Allcott and Wozny (2014) find that consumers fully value the discounted future fuel costs in their purchase decisions, other research indicates that, when deciding on whether to purchase a more fuel-efficient car, consumers tend to calculate the expected savings in fuel costs only for about three years (see Greene et al., 2005, 2013; Kilian and Sims, 2006).

Another phenomenon identified by the literature is the policy-induced substitution between petrol and diesel cars. Diesel engines are typically more efficient than petrol engines. Hence, when Ireland differentiated its purchase and annual road taxes according to CO_2 emission intensities, sales of diesel cars increased, particularly at the expense of large petrol cars (Hennessy and Tol, 2011; Leinert et al., 2013; Rogan et al., 2011). In addition to contributing to a reduction in average CO_2 emissions, this unanticipated shift towards diesel cars caused an increase in NO_X emissions (Leinert et al., 2013). Similar effects have been found in Norway, where a vehicle acquisition tax reform caused a 23 percentage point increase in the diesel market share (Ciccone, 2015).

All research discussed above analyzes the effect of specific vehicle tax policies in a single country. Hence, these papers cannot control for year-specific effects and the results are not easily generalizable. Specifically, single-country estimates may conflate domestic policies with external changes, e.g. EU-wide developments such as efficiency improvements brought by the EU directive 443/2009 on CO_2 standards.[7] In our empirical strategy, we can identify the fiscal effects as year fixed effects absorb the effects of the common policies and technological developments. That is, our empirical analysis does not consider a single-event in one country, yet studies more broadly the fiscal treatment of car purchases and ownership in relation to car emissions. There are some previous cross-country and panel-data studies on the effect of fuel prices on fuel efficiency (Burke and Nishitateno, 2013; Klier and Linn, 2013). The

[6]Consumer myopia, also known as nearsightedness, captures the notion that boundedly rational consumers do not exploit all available information equally, and tend to give more weight to short-term costs and benefits (DellaVigna, 2009).

[7]For instance, Mabit (2014) argues that in Denmark, the biggest contribution to the sales of fuel-efficient cars is probably not the 2007 tax reform, but technological improvements.

effect of the registration and road tax level on car purchases is previously studied in Ryan et al. (2009), who use a panel structure for EU countries. They conclude that vehicle taxes, notably registration taxes, are likely to have significantly contributed to reducing CO_2 emission intensities of new passenger cars. Ryan et al. (2009) focus on the average level of registration taxes in a country.[8] We take this analysis one step further by constructing measures of the CO_2 sensitivity in addition to the level of registration and road taxes. This allows us to exploit differences between EU countries in the stringency and timing of CO_2-related vehicle fiscal policies. An important part of our study is thus a more comprehensive characterization of the vehicle tax system that can be used to compare differences across countries and changes over time, based on a large dataset of country-year-vehicle-specific prices inclusive and exclusive of taxes.

6.3 Model

We illustrate the effect of vehicle purchase taxes on the average emission intensity with a simple model. We consider two car types. A representative consumer[9] maximises (expected future) utility u dependent on the current purchase of cars, q_1 and q_2, and income m net of purchase expenditures x:

$$\max_{q_1,q_2} u\left(q_1,q_2,m-x\right) \text{ s.t.} p_1^c q_1 + p_2^c q_2 = x, \tag{6.1}$$

where p_i^c are costs per quantity, including registration taxes as well as future variable costs and annual taxes. The utility function satisfies the standard assumptions on continuity, differentiability, positive derivatives, and concavity. We also assume that both types are normal goods (increasing consumption with increasing income, decreasing consumption with increasing prices) and that the total budget for cars, x, increases in total income, m.

We do not model consumers' care about the environmental performance of cars as such (see Achtnicht (2012) for an analysis along those lines), but focus on the effects of government instruments geared to direct consumers' choices. We assume

[8]Note that Ryan et al. (2009) weigh the registration tax measure by vehicle sales, so that in their analysis the right-hand-side variable depends on policy outcomes. To prevent dependency of right-hand variables on policy outcomes, we construct tax measures that do not use sales for weighing; see footnote 15.

[9]We consider the aggregate level and treat the number of cars as a continuous variable.

that the tax is fully shifted to consumers,[10] so that the consumer price of cars is

$$p_i^c = (1 + \tau_i)\, p_i^p, \tag{6.2}$$

where τ_i is a type-specific ad valorem tax and p_i^p is the producer price. The tax τ_i consists of a uniform component φ and an environmental component, where θ is a relative weight of the environmental component. The two car types have different emission intensity, say grams of CO_2 per km, which we denote by β_i. Without loss of generality, let $\beta_2 > \beta_1$, for example because car type 2 is more spacious, has more weight, or is more fancy. The type-specific tax becomes:

$$\tau_i = \varphi + \theta\beta_i. \tag{6.3}$$

We are interested in the effect of changes in car taxes on the average CO_2 intensity of the car fleet, which we define as

$$B = \frac{\beta_1 q_1 + \beta_2 q_2}{q_1 + q_2}. \tag{6.4}$$

Policy can change the uniform component of the car tax, φ, the environmental component, θ, or both. We define the average car-tax, given by

$$T = \frac{\tau_1 q_1 + \tau_2 q_2}{q_1 + q_2} = \varphi + \theta B, \tag{6.5}$$

so that we can study shifts in the tax structure while keeping a constant overall tax rate. It is intuitive that an increase in the weight of car-feature θ, while keeping the average tax rate T constant, will decrease the average emission-intensity of the cars:

Proposition 6.1. *An increase in the weight of environmental performance in taxes, ϑ, while keeping average total taxes T constant, will decrease the average CO_2 intensity B:*

$$\frac{dB}{d\theta} < 0 \tag{6.6}$$

Proof. The policy in the proposition increases the price of the relatively emission-intensive car and decreases the price of the more fuel-efficient car. The result follows immediately from the assumption that both car types are normal goods. □

[10]We abstract here from strategic pricing by car manufacturers. Though this is important as a mechanism, our results below will hold as long as the car manufacturers pass-through part of taxes. In general, ad valorem taxes may be under- or overshifted under Bertrand competition with differentiated products (Anderson et al., 2001). If car manufacturers differentiate prices between countries so as to partly compensate taxes, the effect of fiscal measures will be reduced, and our coefficients will become smaller and less significant.

Thus tilting the car taxes to become more CO_2-dependent will make the car fleet more CO_2-efficient. The effect of an overall car tax increase is more subtle. A price increase has a similar effect as an income reduction. Car types with a high income elasticity thus tend to lose market share when taxes uniformly increase. The impact of the tax level therefore depends on the comparative income elasticity of the two car types.

Proposition 6.2. *If the environmental tax component ϑ is sufficiently small, then feature B decreases with an overall tax increase φ (or equivalently an increase in T) if and only if the less fuel-efficient car type has higher income elasticity:*

$$\frac{dB}{d\varphi} < 0 \Leftrightarrow \frac{\partial q_2}{\partial m}\frac{m}{q_2} > \frac{\partial q_1}{\partial m}\frac{m}{q_1} \tag{6.7}$$

Proof. Consider $\frac{\partial q_2}{\partial m}\frac{m}{q_2} > \frac{\partial q_1}{\partial m}\frac{m}{q_1} \leftrightarrow \frac{\partial q_2}{\partial x}\frac{\partial x}{\partial m}\frac{m}{q_2} > \frac{\partial q_1}{\partial x}\frac{\partial x}{\partial m}\frac{m}{q_1} \leftrightarrow \frac{\partial q_2}{\partial x}\frac{m}{q_2} > \frac{\partial q_1}{\partial x}\frac{m}{q_1} \leftrightarrow \frac{\partial q_2}{\partial x}\frac{x}{q_2} > \frac{\partial q_1}{\partial x}\frac{x}{q_1}$. An increase in φ constitutes an equiproportional increase in the prices of all cars when $\theta = 0$. Since cars are a normal good (which we use in the middle equivalence), an increase in car prices decreases demand for all types. When $\theta = 0$, an increase in φ is equivalent to a decrease in the budget for cars. Because type 2 has a larger income- and budget elasticity $\left(-\frac{\partial q_2}{\partial \varphi}\frac{\varphi}{q_2} > -\frac{\partial q_2}{\partial x}\frac{x}{q_1}\right)$, the average CO_2 intensity B goes down. By continuity, the result also holds for θ sufficiently small. □

The typical hypothesis asserts that demand for luxurious cars is more income-elastic. Mannering and Winston (1985) find that large and mid-size cars have a higher income elasticity on average than compact cars. A meta-analysis by Goodwin et al. (2004) finds that fuel consumption is more income-elastic than traffic volume, which is consistent with the idea that wealthier consumers buy less fuel-efficient cars. Heffetz (2011) documents larger income elasticities for more visible consumption categories for a wide array of expenditures.

Larger cars, which are also emission-intensive, tend to be more comfortable. For example, they offer more storage and lower occupant fatality rates in vehicle-to-vehicle crashes – attributes that are more easily dispensable than a car's basic transportation service. The proposition predicts a decrease in the average pollution intensity if the uniform tax φ increases. Indeed, Bordley (1993) obtains higher (Hicksian) price elasticities for luxury car segments, which together with their higher income elasticity also corroborates Proposition 6.2. The above literature is also consistent with our own finding reported in Table 6.6.

For high environmental taxes θ the effect may be reverted, as an increase in the uniform tax rate φ can then represent a fall in the relative price of less fuel-efficient cars. As we will see however, the relative importance of the environmental component in total car taxes is modest in European countries, so that the proposition's condition seems to apply.

In the next section, we construct the country-tax variables. The variable construction will closely follow the decomposition in equation (3), where, θ and β_i will respectively be the average country-year-specific tax rate, and the increase in the tax rate (θ) for a given increase in car-specific CO_2 emissions (β_i). We then test Propositions 6.1 and 6.2 by estimating the effect of the tax system variables (φ and θ) on the average CO_2 intensity of newly purchased vehicles (B in equation 6.4).

6.4 Data

Here we describe the data used for the empirical analysis. The dependent variable of interest is the average CO_2 intensity of newly purchased vehicles, which depends on substitution patterns between more and less fuel-efficient cars, but also on common fuel efficiency improvements over all cars, which in our econometric strategy is absorbed by time fixed effects. The main explanatory variables are fuel taxes and the two coefficients used in the model in Section 6.3: the average level of registration and annual road taxes, and their CO_2-sensitivity. Here, we define the vehicle registration tax as all one-off taxes paid at the time the vehicle is registered, which is usually the time of acquisition. For road taxes, we include all annual recurrent taxes of vehicle ownership. We construct these data for each country, year, and fuel type in our sample using a detailed database with vehicle registration taxes and road taxes at vehicle-country-year level.

6.4.1 Data sources

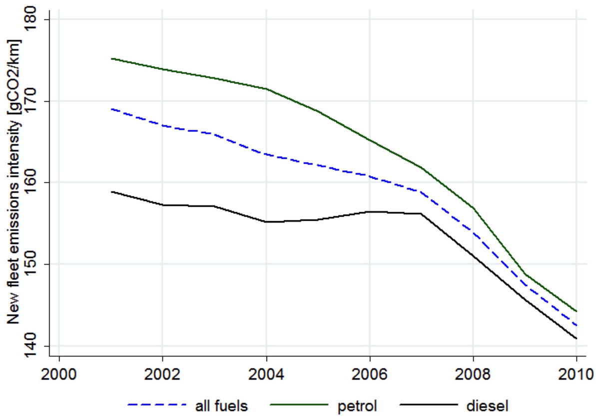
Our first data source is a set of manufacturer price tables as supplied by the European Commission (2011a). These tables form an unbalanced panel with 11930 observations on prices and registration taxes, across 204 car types, 20 countries (15 countries up to 2005) over the years 2001-2010. Petrol cars make up about two-third of all observations.[11] This source includes the retail price data per country inclusive and exclusive of the registration tax, and allows us to construct the vehicle-country-year-specific registration tax. As of 2011, the European Commission no longer collects data on automobile prices. As these prices are a crucial part of our analysis, our series end in 2010. Next we construct vehicle-country-year-specific road taxes using

[11] Dvir and Strasser (2014) use the same data for an analysis of manufacturers' price dispersion on the EU car market.

our second data source: the ACEA (2010) tax guides and the European Commission (2011a) passenger car dataset. We also take information on fuel taxes from the ACEA tax guides. Because most cars are petrol or diesel, we restrict our sample to these two fuel types.[12]

The dataset does not contain car-specific sales data. The dataset from Campestrini and Mock (2011) contains information on the CO_2 intensity of the newly purchased diesel and petrol cars (CO_2 emissions in g/km, weighted by sales) and the shares of diesel cars (see Figure 6.E.1 in Appendix 6.E). We have this information for the EU15 countries, from 2001-2010. As shown in Figure 6.1, over this period, CO_2 intensity has come down remarkably, albeit with sizeable differences across countries (Figure 6.2). Lastly, data on nominal per capita GDP is taken from Eurostat (2014). We deflate all prices (sales prices, taxes, GDP) using a common EU15 price deflator.[13]

Figure 6.1: CO_2 emission-intensity for new cars, EU15 average

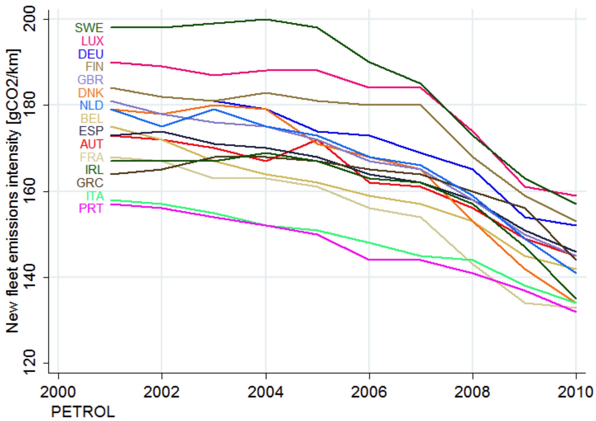


Source: Campestrini and Mock (2011)

[12]This poses no problem for the construction of the country tax proxies, as these are based on an unweighted sample of most-sold cars.

[13]The deflator is constructed using a weighted average of the EU15 countries' individual inflation rates, according to standard EU methodology. See https://www.ecb.europa.eu/stats/prices/hicp/html/index.en.html.

Figure 6.2: CO_2 emission-intensity for new petrol cars, by country



Source: Campestrini and Mock (2011)

6.4.2 Constructing country average and CO_2 sensitivity of car taxes

Countries have widely divergent rules for registration and road taxes. In some countries, vehicle registration taxes are based on CO_2 emissions, in others, the cylindrical content is used to compute the tax, or the sales price of the car. In many instances, registration taxes combine multiple variables. Rules for annual road taxes vary even more across Europe. Some countries base their annual tax on a car's engine power (in kW or hp), while other countries use cylinder capacity, CO_2 emissions, weight and exhaust emissions. In addition to the dispersion between countries, for both registration and road taxes, many countries have changed their policies over the period 2001-2010; they adopted (temporary) discounts for fuel-efficient cars, or additional charges for cars exceeding specified standards.[14] We compare tax systems across countries by characterizing each country's tax system at year t by the two coefficients used in our model in Section 6.3. The first coefficient describes the country-year average tax, the second the CO_2 sensitivity of the tax. Both variables are computed for both the registration and road tax, and for petrol and diesel. We thus construct 8 variables that characterize a country's vehicle tax system for a given year.

We now provide the details. Let $CO2_{it}$ be the CO_2 intensity of car-type i in year t, τ_{cit} the (registration or road) (percentage) tax in country c, and let δ_{cit} be the index $\{0,1\}$ identifying whether the data are available for country c. For the sake of exposition, we do not use subscripts for fuel and tax type (registration versus road). We

[14] Van Essen et al. (2012) provides a detailed overview of the of the parameters used for the calculation of the registration and road taxes, as well as the tax for a representative vehicle, across the European countries.

construct the country-specific CO_2 intensity and tax rate for the typical car *offered*[15] on the market (denoted by bars on top over the variables):

$$\overline{CO2}_{ct} = \frac{\sum_i \delta_{cit} CO2_{it}}{\sum_i \delta_{cit}}, \tag{6.8}$$

$$\overline{\tau}_{ct} = \frac{\sum_i \delta_{cit} \tau_{cit}}{\sum_i \delta_{cit}}. \tag{6.9}$$

That is, the typical car for a country has emissions $\overline{CO2}_{ct}$ and pays a tax rate $\overline{\tau}_{ct}$. We subsequently calculate the CO_2 sensitivity of the tax by comparing how much, for each country-year, the vehicle-specific tax increases for a given increase in the vehicle's CO_2 emissions, on average, and weighted:

$$CO2TAX_{ct} = \frac{\sum_i \delta_{cit} w_{cit} \left(\tau_{cit} - \overline{\tau}_{ct}\right)}{\sum_i \delta_{cit} w_{cit} \left(CO2_{cit} - \overline{CO2}_{ct}\right)}. \tag{6.10}$$

Where weights are given by the deviation of the vehicle CO_2 intensity from the typical CO_2 intensity:

$$w_{cit} = \left(CO2_{cit} - \overline{CO2}_{ct}\right). \tag{6.11}$$

The squared weights ensure that the denominator in (6.10) is strictly positive, and that the CO_2 sensitivity is mainly determined by the tax-differences between the fuel-efficient and fuel-intensive cars.

Yet, if we want to determine a country's tax pressure and compare between countries, we should not consider the tax of the typical car for that country, but the tax for a typical car that is the same over all countries. Thus, we construct the (virtual) tax rate that would apply to a car with a CO_2-emission profile $\check{CO}2_t$ that is typical for the set of all countries:

$$\check{CO}2_t = \frac{\sum_{c,i} \delta_{cit} CO2_{it}}{\sum_{c,i} \delta_{cit}}, \tag{6.12}$$

$$TAX_{ct} = \overline{\tau}_{ct} + CO2TAX_{ct} \left(\check{CO}2_t - \overline{CO2}_{ct}\right). \tag{6.13}$$

The above method generates 8 variables for each country-year pair. The precise interpretation depends on the details of the input variables, $CO2_{it}$ and τ_{cit}. If CO_2 emissions are measured linearly in [gCO_2/km], and taxes in euros, then $\overline{\tau}_{ct}$ is the tax in euros [€] paid for the car with a typical CO_2-emission profile while $CO2TAX_{ct}$ is the increase as measured in [€/(gCO_2/km)]. If taxes are measured ad valorem, then

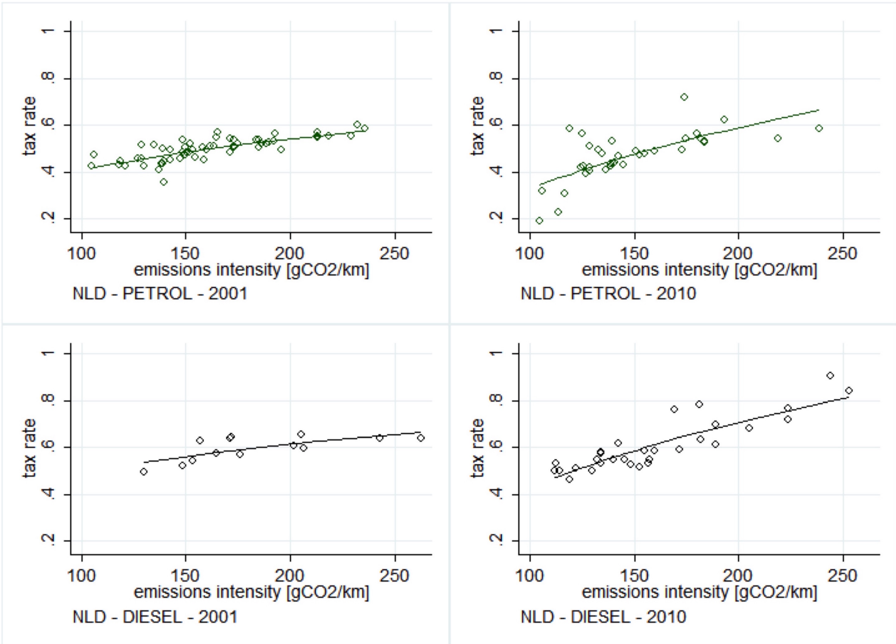
[15]In the construction of our tax system variables we do not weigh by sales, to prevent our description of the tax system from being contaminated by the subsequent effects of that same tax system. The tax system may of course affect sales, and thereby the CO_2 emission intensity of newly purchased cars. This is discussed in the appendix, Section 6.6.

$\bar{\tau}_{ct}$ is the typical car tax rate in percentages while $CO2TAX_{ct}$ is the increase in the tax rate per gCO_2/km. Our preferred specification uses the logarithm of one plus tax rates and the logarithm of CO_2 emissions, so that variables are interpretable as elasticities, and (with time fixed effects) the construction is independent of price levels. In this case, a decrease of the variable $\bar{\tau}_{ct}$ of 0.01 means that the tax rate for the typical car has fallen by 1%. If two car types are completely identical (including prices at the factory gate), but one car is 10% more fuel-efficient, then the consumer price of the more fuel-efficient car is $0.1 \times CO2TAX$ per cent below the consumer price of the more fuel-intensive car. All estimations in the main text are based on the double-log variables. We have reproduced our results for a linear model, which is presented in the appendix, Section 6.B. The appendix also provides the equations with more elaborate references to the details of taking logarithms.

Expressions (6.12) and (6.13) can directly be connected to equation (6.3) of the stylized model. Here, TAX_{ct} resembles the country-year-specific general tax rate (φ), with $CO2TAX_{ct}$ the increase in the tax rate for a given increase in vehicle-specific CO_2 emissions (θ).

Figure 6.3 below shows a typical breakdown of the vehicle registration tax rate in its level and CO_2 sensitivity. The charts show the registration taxes paid in the Netherlands, in 2001 (left) and 2010 (right), for a series of petrol (upper) and diesel (lower) cars. The dots are observations for individual car types, described at the beginning of Section 6.4.1. The lines present the 'predicted' tax rates based on the two proxy variables TAX and$CO2TAX$ constructed above. As is immediately visible from the left and right panels, the tax rate has become more sensitive to CO_2 emissions between 2001 and 2010, that is, the slope of the line has increased. Figure 6.4 shows the decomposition of the tax in its average tax rate and the CO_2 tax over the years 2000-2011. The levels of the predicted tax in the panels of Figure 6.3 correspond to the values in the left panel in Figure 6.4, while the slope of the predicted taxes in the panels of Figure 6.3 correspond to the values in the right-panel of Figure 6.4. The average registration tax rate for petrol cars started at about 50 per cent, and sharply dropped in the last years reaching about 47 per cent in 2010 and 40 per cent in 2011. The CO_2 sensitivity of registration taxes however has increased substantially for both petrol and diesel cars between 2000 and 2011. Figure 6.3 (panel in top-right corner) illustrates this shift. Various tax breaks for fuel-efficient cars came into force, which substantially increased the CO_2 sensitivity of taxes, from about 10% to 25% (see Figure 6.4, right panel), but at the same time reduced the average tax. All other things equal, in 2011, the after-tax price decreases by about 3% if a car is 10% more fuel-efficient. The charts in Figure 6.4 also show that, in the Netherlands, taxes for diesel cars are persistently above those for petrol cars;[16] in our results section, we will come back to the effect of tax differentiation between petrol and diesel cars.

Figure 6.3: Taxes per vehicle, dependent on CO_2 emission intensity, Netherlands



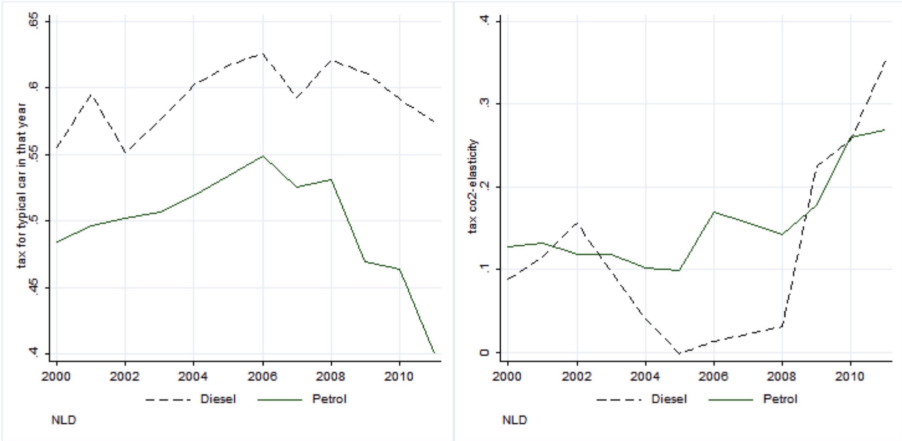
Registration taxes for 2001 (left panels) and 2010 (right panels), petrol (upper) and diesel (lower). Taxes are measured relative to car prices.

Table 6.1 below provides some additional summary statistics and the means for the first and last sample years.[17] Over 2001-2010, the average registration tax for diesel cars decreased from 46 to 40 per cent (see footnote at table) while for petrol cars the registration tax rate decreased from an average of 39 to 35 percent. The extra tax paid for purchasing a high-emission vehicle has increased substantially, however. In 2001, purchasing a diesel vehicle with 10 percent higher emissions increased the registration tax rate by approximately 0.6 percentage point on average. By 2010, this has increased to 1.4 percentage point. For some countries, the elasticity of the registration tax rate with respect to emissions is negative. This does not directly imply that fewer taxes are paid for polluting vehicles. If a more polluting car is more expensive, then the absolute tax paid can increase while the tax rate paid can

[16]The Netherlands is atypical in the sense that registration taxes and fuel taxes are used as instruments to segregate the car market. Diesel fuel taxes are low (relative to petrol) while diesel registration taxes are high (relative to petrol). The tax scheme intends to separate long-distance drivers (who buy diesel cars) from short-distance drivers (who buy petrol cars).

[17]Tables 6.E.1a and 6.E.1b in the appendix provide a more detailed overview of the country-specific constructed registration and road taxes for the years 2001 and 2010.

Figure 6.4: Estimated registration taxes, Netherlands



Registration tax levels for typical vehicle (left), and tax dependence on CO_2 emission intensity (right), for the Netherlands, 2000-2011, petrol (green solid) and diesel (black dashed)

decrease.[18]

In 2001, the road tax rate is on average 2 percent of the vehicle's (tax-exclusive) purchase price, for both diesel and petrol cars. Several countries have no annual road tax. The average elasticity of the annual tax rate with respect to CO_2 emissions has changed from being negative in 2001 to a positive value in 2010. Overall, there is a slight pattern towards lower road tax rates, combined with a greater dependence of the tax rate on the emissions of a car.

Table 6.1: Summary statistics for constructed tax levels and CO_2 sensitivity for EU15

		2001-2010				2001	2010
		Mean	Std. dev.	Min	Max	Mean	Mean
Vehicle registration tax rate	Diesel	0.35	0.24	0.14	1.12	0.38	0.34
	Petrol	0.33	0.21	0.14	0.98	0.33	0.30
Vehicle registration tax rate, CO_2 sensitivity	Diesel	0.07	0.13	-0.22	0.66	0.06	0.14
	Petrol	0.10	0.14	-0.08	0.53	0.10	0.13
Road tax rate	Diesel	0.02	0.02	0.00	0.07	0.02	0.02
	Petrol	0.02	0.01	0.00	0.09	0.02	0.02
Road tax rate, CO_2 sensitivity	Diesel	-0.004	0.01	-0.07	0.04	-0.015	0.003
	Petrol	-0.004	0.02	-0.1	0.05	-0.011	0.004

All numbers are based on a logarithmic representation. The average tax rate for diesel cars in 2001 was thus exp(0.38)-1=0.46. See Table 6.B.1 in Appendix 6.B, for the tax levels and CO_2 sensitivity based on the linear model.

[18]This can happen if part of the registration tax is independent of the car price. Indeed, results from the linear model presented in the appendix show that in all countries, tax levels (weakly) increase for more CO_2 emission-intensive vehicles (see Table 6.B.1).

Vehicle fiscal measures are correlated, also when we take out country and time fixed effects. Petrol and diesel registration taxes move in tandem, both for the levels and CO_2-sensitivity. The same applies to the annual taxes, where correlations exceed 80%.[19] Petrol and diesel fuel taxes are also positively correlated. The year fixed effects separate fuel price developments from fuel tax changes. There is almost no correlation between the three groups of tax instruments. For annual taxes, we see a very strong negative correlation between the level of annual taxes and its CO_2 sensitivity, implying that the set of annual taxes are strongly multi-collinear, so that we must be careful when interpreting individual coefficients for annual taxes.[20]

6.5 Econometric strategy

The benchmark model estimates the dependence of the CO_2 intensity of the new car fleet in country c in year t (as in Figure 6.2), separately for diesel and petrol, on the two dimensions of the registration car taxes: its level and its CO_2 sensitivity

$$CO2int_{ct} = \alpha_{1c} + \alpha_{2t} + \beta_1 TAX_{ct} + \beta_2 CO2TAX_{ct} + \sum_k \pi_k Z_{ckt} + \varepsilon_{cit}, \tag{6.14}$$

where α_{1c} and α_{2t} are country and time fixed effects, and the country-time-specific control variables Z include income and gasoline taxes.[21,22] For our preferred model, we use logarithms for the dependent variable. In the linear model (see Appendix, Section 6.B), the dependent variable is measured in average grams of CO_2 emissions per km.

We add convergence patterns through the control variable, through

$$Z_{c1} = CO2int_{c0}, \tag{6.15}$$

$$Z_{c2t} = (year_t - 2001) \times CO2int_{c0}, \tag{6.16}$$

where $CO2int_{c0}$ is the CO_2 intensity of the new fleet in the base year 2001. Convergence between countries is measured through a negative coefficient for the inter-

[19]See Table 6.E.2 in the appendix for details

[20]The negative correlation between the level of annual taxes and its CO_2 sensitivity is 'natural' in the following sense. If the level of annual taxes increase, typically they increase less than proportional with the car's size, weight and price. Thus, annual taxes have a tendency to be regressive. This is picked up by a negative coefficient for the CO_2 sensitivity.

[21]The fuel tax is calculated for each country-year-fuel type by fuel: $tax = \ln(1 + \text{fuel tax level}/\text{fuel price})$, where we take the fuel price as the average fuel price across the countries.

[22]In the Appendix 6.D, we also check robustness for other variables to control for the economic crisis. We do not control for the effects of carmaker-specific differences in fuel efficiency improvements interacted with market share differences between countries.

action term (6.16). We assume there is no systematic correlation between observed fiscal vehicle policies and unobserved policies such as vehicle retirement plans that could induce omitted variable bias.

We first estimate the model for both fuel types jointly and separately,[23] with and without the annual taxes. This allows us to assess the effect of tax levels and CO_2-intensities on the emission intensity of diesel cars, petrol cars and the average fleet. We then attempt to decompose these effects into effects stemming from substitution between fuel types, effects from substitution between large and small cars, and effects from increased efficiency holding the car attributes constant. For this decomposition, we first add diesel share, average mass and average horsepower to the control variables Z. Next, we replace $CO2INT_{c0}$ by the corresponding base year variable as the dependent variable in (6.14), leaving all other variables unchanged.

6.6 Results

6.6.1 Fuel type-specific effects

Table 6.2 displays the results for the CO_2 intensity for diesel and petrol cars respectively. Starting with the CO_2 intensity of new diesel cars, we find a clear significant effect of registration taxes on CO_2 emissions. Especially the CO_2 sensitivity is an effective instrument to change the characteristics of newly bought vehicles: a 1% increase in CO_2 sensitivity of the registration tax reduces the CO_2 intensity by about 0.1 percent (second row Table 6.2). We find no significant effect for road taxes on the emissions by diesel cars. Higher diesel fuel tax rates increase the fuel efficiency of newly acquired diesel vehicles, as expected (Burke and Nishitateno, 2013). In addition, we find higher CO_2 intensities with increasing income and a clear convergence pattern between EU countries.

For petrol vehicles, the pattern is similar. The effect of CO_2 tax sensitivity is negative and significant: the average CO_2 sensitivity in 2010 (0.13) reduces the CO_2 intensity of new bought cars by about 2 percent. An increase in the registration tax level reduces the CO_2 intensity of newly acquired vehicles, but the coefficients are insignificant. For petrol vehicles, annual road taxes receive a significant coefficient, yet the signs are opposite to what is expected.[24] Fuel taxes do not show a significant effect for petrol car purchases.

[23] In the latter case, we take the average and difference across fuel types for all tax variables, as opposed to the only diesel or petrol-specific ones.

[24] This may in part be explained by the strong negative correlation between the level and CO_2 sensitivity of annual taxes (see Table 6.E.2 in the Appendix), which may introduce bias. In a regression where either of the annual tax measures is excluded, the coefficient on the remaining measure is greatly reduced and no longer significant.

In our regressions, even though the annual road tax rates enter significantly, excluding them from the regression has only little effect on the coefficient for the other variables. Hence, we can interpret the other coefficients with confidence, and conclude that leaving annual taxes unaccounted for probably does not greatly alter our conclusions.

Table 6.2: Dependence of new car fleet emissions on taxes, per fuel type

Dependent variable	(log) CO_2 intensity diesel		(log) CO_2 intensity petrol	
	(1)	(2)	(3)	(4)
TAX registration	-0.021	-0.027	-0.031	-0.028
CO2TAX registration	-0.099**	-0.095**	-0.140**	-0.136*
TAX road	0.182		1.746**	
CO2TAX road	0.386		1.092**	
Fuel tax rate	-0.304***	-0.303***	-0.057	0.004
(log) income	0.251**	0.233**	0.193***	0.150**
Convergence	-0.051*	-0.048*	-0.028**	-0.030**
Time FEs	Yes	Yes	Yes	Yes
Country FEs	Yes	Yes	Yes	Yes
Observations	150	150	150	150
R-squared within	0.310	0.303	0.347	0.279
R-squared	0.915	0.914	0.973	0.970

Significance: *** p<0.01, ** p<0.05, * p<0.1. Observations are clustered by country. The R-squared within is calculated for the residuals after both time and country FEs.

6.6.2 Aggregate effects

Then consider the overall effect of car taxes on the new fleet emission intensity, as reported in Table 6.3. At first sight, it looks as if registration taxes, and specifically the CO_2 sensitivity, have lost their significance as an important determinant. But this can be explained by the high collinearity between the average and difference of the CO_2 sensitivity of registration taxes.[25] When both the average and difference in CO_2 sensitivity are included in the estimation, this collinearity causes coefficient estimates to be imprecise, and we lose significance. The hypothesis that neither the level, nor the difference in, the CO_2 sensitivity of registration taxes has any effect is strongly rejected, at $p < 0.01$ (bottom part of Table 6.3). If we only include the policy variables that we expect to have the most important effect on the overall fleet's CO_2 intensity, we indeed find a strong significant effect for the average CO_2 sensitivity of the registration tax (third column).

[25] After taking out time and country fixed effects, this correlation equals 0.81.

The average registration tax level does not affect overall CO_2 intensity, yet higher registration taxes for diesel cars relative to petrol cars increase the average CO_2 intensity of new cars. As will be further discussed in the next section, this latter effect can be explained by changes in the diesel share. For a given vehicle performance, diesel cars typically emit less CO_2. Lower overall taxes for diesel cars increase the share of diesel cars and thereby decrease average overall emissions.

By subtracting the log of taxes in 2001 from those in 2010 (6.1) and multiplying the differences with the coefficients in Table 6.3, we find that the changes in registration taxes have reduced the CO_2 intensity of the new cars by 1.3% on average. The overall effects are modest; an explanation is that various countries with a major domestic car industry (France, Germany, Italy, United Kingdom) have relatively low registration taxes that are almost independent of emission intensities. Interestingly, based on the results in Table 6.2, we find that the changes in registration taxes over the period 2001-2010 have caused extant diesel drivers to choose more CO_2-intensive cars on average. For these drivers, the effect of lower registration tax levels in 2010 compared to 2001 dominates the effect of the increased CO_2 sensitivity.

Along the same lines, we find that higher petrol fuel taxes tend to reduce the fleet's emission intensity, while diesel fuel taxes tend to increase average emissions, though the effect is weak.

Table 6.3: Dependence of new car fleet emissions on taxes, aggregated over fuels

Dependent variable	(log) CO_2 intensity overall		
	(1)	(2)	(3)
TAX registration (average)	0.096	0.079	
TAX registration (difference)	0.192*	0.148	0.202**
CO2TAX registration (average)	-0.131	-0.104	-0.131***
CO2TAX registration (difference)	0.003	-0.005	
TAX road (average)	1.381		
TAX road (difference)	1.633*		1.471**
CO2TAX road (average)	0.854*		0.135
CO2TAX road (difference)	0.024		
Fuel tax rate (average)	-0.121*	-0.149	-0.101
Fuel tax rate (difference)	0.127*	0.106	0.076
(log) income	0.158***	0.148***	0.136**
Convergence	-0.029	-0.049**	-0.033*
Time FEs	Yes	Yes	Yes
Country FEs	Yes	Yes	Yes
Observations	150	150	150
R-squared within	0.501	0.394	0.458
R-squared	0.974	0.968	0.971
TAX registration (joint)	0.050	0.092	
CO2TAX registration (joint)	0.000	0.000	
TAX road (joint)	0.146		
CO2TAX road (joint)	0.183		
Fuel tax (joint)	0.086	0.210	0.427

Averages are unweighted averages over the two fuel types. Differences are computed as {diesel}-{petrol}. Significance: *** p<0.01, ** p<0.05, * p<0.1. Observations are clustered by country. The R-squared within is calculated for the residuals after both time and country FEs. The bottom 5 rows report the p-values of the joint significance tests.

6.6.3 Transmission mechanisms

Finally, we present an assessment of the transmission channels through which fiscal car taxes change emissions. Consumers can switch between petrol and diesel cars, in response to tax measures, but within a fuel type, they can also respond to tax measures by switching to lighter cars with less powerful engines, or alternatively, they can choose for cars with more fuel-efficient engines while keeping the preferred car specifications unaffected (Fontaras and Samaras, 2010).

In Table 6.4 we present, for diesel and petrol separately, the effect of fiscal measures on the CO_2 intensity with and without additional controls for diesel share, average vehicle mass and engine power. Columns 1 and 5 show the overall policy effects, conflating the changes in the fleet by those consumers that do not change fuel type, with changes brought by consumers who switch to the other fuel type.[26]

[26] To allow easy comparison, columns 1 and 5 in Table 6.4 reproduce Table 6.2 columns 1 and 3 respec-

Columns 2 and 6 control for changes in the diesel share. Comparing column 1 to 2, and column 5 to 6, then reveals the effect of consumers switching between fuels at the margin, captured by the coefficient for the diesel share. Columns 2 and 6 still conflate the policies' effects through car specifications (weight and power) with those reached through improved efficiency while keeping car weight and power constant. Controlling for these in columns 4 and 8 then separates the efficiency effect from the effects through car specifications. We discuss the effects of fiscal measures on CO_2 emissions through the diesel share and car specifications in turn.[27]

tively.

[27] Note that even though transmission channels included in columns 2-4 and 6-8 are endogenous, in the sense that they are dependent on policy variables and income, this endogeneity is not related to potential reverse causality.

Table 6.4: Transmission of fiscal policy to CO_2 intensity

Dependent variable	(log) CO_2 intensity diesel				(log) CO_2 intensity petrol			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
TAX registration	-0.021	-0.165	0.010	-0.024	-0.031	-0.087	0.018	-0.016
CO2TAX registration	-0.099**	-0.046	-0.046***	-0.038**	-0.140**	-0.123**	-0.009	-0.002
TAX road	0.182	-0.327	0.030	-0.075	1.746**	1.992***	0.413	0.609*
CO2TAX road	0.386	-0.232	0.008	-0.108	1.092**	1.095***	0.241	0.265
Fuel tax rate	-0.304***	-0.224**	0.030	0.032	-0.057	0.025	0.000	0.047
Diesel share		-0.154***		-0.037		-0.070**		-0.042***
Mass (log)			0.846***	0.773***			0.539***	0.513***
Horse power (log)			0.284**	0.287***			0.139**	0.142**
(log) income	0.251**	0.129*	-0.001	-0.015	0.193***	0.128**	0.018	-0.017
Convergence	-0.051*	-0.03	-0.052***	-0.048***	-0.028**	-0.019	-0.011**	-0.006
Time FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	150	150	149	149	150	150	150	150
R-squared within	0.310	0.422	0.802	0.807	0.347	0.395	0.783	0.800
R-squared	0.915	0.929	0.976	0.976	0.973	0.975	0.991	0.992

Significance: *** p<0.01, ** p<0.05, * p<0.1. Observations are clustered by country. The R-squared within is calculated for the residuals after both time and country FEs.

6.6.3.1 Diesel share

Table 6.5 presents the direct effect of fiscal measures on the diesel share. As we see in this table, a higher CO_2 sensitivity of registration taxes increases the share of diesel cars. Buyers who decide to acquire a diesel car as a substitute for a petrol car typically buy diesel cars that are smaller compared to the average diesel car, while they substitute away from petrol cars that are large compared to the average petrol car (see Rogan et al., 2011; Hennessy and Tol, 2011; Leinert et al., 2013). This finding in the literature is supported by our Table 6.4; we find that the diesel share has a negative and significant coefficient in both columns 2 and 6 (Table 6.4), while these coefficients become substantially smaller once we correct for the average mass and horsepower (columns 3 and 7). These consumers who substitute diesel cars for petrol cars thereby reduce the average emissions of both diesel and petrol cars. Indeed, a closer look at our data (not shown here) shows that diesel cars are on average 20 percent heavier compared to petrol and the average weight for both diesel and petrol cars decreases with an increase in the diesel share (see also column 1 and 3 in Table 6.6). These observations jointly indicate that part of the emission reduction of new cars in the EU has likely been achieved by lower registration taxes (as observed in Table 6.1), which translated in an increased share of diesel cars (Table 6.5), which are typically more fuel-efficient than petrol cars, and thus in turn decreases the CO_2 intensity of the average car. In addition to the average level of registration taxes across fuels, higher registration tax levels for diesel cars compared to petrol cars tend to reduce the diesel share (see the second row in Table 6.5), as does a lower average CO_2 sensitivity of registration taxes (third row in Table 6.5). For fuel taxes, we find that higher diesel (petrol) fuel taxes reduce (increase) the diesel share. Finally, higher road taxes for diesel cars reduce the diesel share.[28]

[28] As before, the road tax level and CO_2 sensitivity are strongly negatively correlated, which may bias results. Re-estimating the model excluding either the level or CO_2 sensitivity of road taxes changes neither the sign nor significance of the individual effects, yet reduces the size of the effect by more than 80 percent.

Table 6.5: Transmission of fiscal policy to CO_2 intensity; diesel share

Dependent variable	Diesel share		
	(1)	(2)	(3)
TAX registration (average)	-0.978***	-0.815**	
TAX registration (difference)	-0.684	-0.687*	-0.876**
CO2TAX registration (average)	0.348**	0.288	0.496**
CO2TAX registration (difference)	0.076	0.114	
TAX road (average)	-2.226		
TAX road (difference)	-13.34***		12.00**
CO2TAX road (average)	-1.147		0.112
CO2TAX road (difference)	-0.81		
Fuel tax rate (average)	0.762**	0.904***	0.695**
Fuel tax rate (difference)	-0.802***	-0.704	-0.696***
(log) income	-0.596***	-0.693***	-0.506***
Time FEs	Yes	Yes	Yes
Country FEs	Yes	Yes	Yes
Observations	150	150	150
R-squared within	0.640	0.333	0.566
R-squared	0.958	0.923	0.950
TAX registration (joint)	0.007	0.022	
CO2TAX registration (joint)	0.008	0.006	
TAX road (joint)	0.010		
CO2TAX road (joint)	0.567		
Fuel tax (joint)	0.000	0.001	0.005

Averages are unweighted averages over the two fuel types. Differences are computed as {diesel}-{petrol}. Significance: *** p<0.01, ** p<0.05, * p<0.1. Observations are clustered by country. The R-squared within is calculated for the residuals after both time and country FEs. The bottom 5 rows report the p-values of the joint significance tests.

6.6.3.2 Mass and horsepower

Columns 3, 4, 7 and 8 of Table 6.4 confirm that emission intensities are higher when cars are larger and have more powerful engines. Table 6.6 presents the effect of fiscal measures on average mass and engine power. Adding mass and horse power reduces the (absolute) coefficient on registration taxes in columns 3 and 7, and 4 and 8 of Table 6.4 compared to columns 1 and 5, and 2 and 6, respectively, suggesting that registration tax levels affect average mass or engine power of newly purchased vehicles. The effect is, however, statistically insignificant in Table 6.6, so that we evaluate the evidence as weak. We find no effect for the CO_2 sensitivity of diesel registration taxes on average mass and engine power of new diesel vehicles (column 1 and 2, second row, in Table 6.6), but a strong significant effect for the CO_2 sensitivity of petrol registration taxes. Taken together with the negative effect of the CO_2 sensitivity of diesel registration taxes on diesel CO_2 intensity, a possible interpretation is that higher and more CO_2-sensitive diesel registration taxes push consumer purchase choices towards the technology frontier, providing the same qualities (mass and horse power) to the consumers, at lower CO_2 emissions. For petrol cars, the effects of registration taxes appear to be transmitted through the car features: higher (CO_2 sensitivity of) registration taxes reduce the average mass and horse power of newly purchased vehicles, even among consumers who do not switch to diesel cars in response to the tax changes. There is less indication of a technology effect, and more evidence of switch in the type of cars bought by petrol-car consumers.

We note that the effects of income on CO_2 intensities appear to be fully transmitted through car features, both for diesel and petrol cars; the effects of income on CO_2 intensity in Table 6.5 are no longer significant when we control for mass and horsepower. Results suggest that increasing income is mainly used to increase the level of desirable features. We thus find no evidence that consumers use income increases to purchase more environmentally friendly cars. For diesel cars, the effect of diesel fuel taxes is also fully transmitted through the car features.

Table 6.6: Transmission of fiscal policy to CO_2 intensity; vehicle mass and horse power

Dependent variable	Diesel		Petrol	
	Mass	Horse power	Mass	Horse power
	(1)	(2)	(3)	(4)
TAX registration	-0.014	-0.185	-0.098	-0.231
CO2TAX registration	0.002	-0.024	-0.160***	-0.268***
TAX road	-1.528	0.759	1.654**	3.615**
CO2TAX road	-0.696	0.496	1.073**	1.911**
Fuel tax rate	-0.235*	-0.297	-0.03	0.024
Diesel share	-0.086**	-0.105**	-0.042	-0.046
(log) income	0.116**	0.19	0.161**	0.408***
Convergence	-0.003	-0.007	-0.014	-0.009
Time FEs	Yes	Yes	Yes	Yes
Country FEs	Yes	Yes	Yes	Yes
Observations	150	150	150	150
R-squared within	0.195	0.205	0.324	0.390
R-squared	0.876	0.929	0.952	0.965

Significance: *** p<0.01, ** p<0.05, * p<0.1. Observations are clustered by country. The R-squared within is calculated for the residuals after both time and country FEs.

6.7 Discussion

We find empirical evidence that fiscal vehicle policies significantly affect emission intensities of new bought cars. Increasing CO_2-sensitivity of registration taxes lead to the purchase of more fuel-efficient cars. A one percent increase in the CO_2 sensitivity of vehicle purchase taxes reduces the CO_2 intensity of the average new vehicle by about 0.1 percent. The changes in registration taxes from 2001 to 2010 have reduced the CO_2 emission intensity of the average new car by 1.3%. The diesel-petrol substitution induced by changes in the relative taxes for diesel versus petrol cars is an important factor for the average fleet's fuel efficiency. We also find higher CO_2 intensities with increasing income and a clear convergence pattern between EU countries.

This paper is one of the first including annual road taxes, in addition to registration and fuel taxes, in the analysis of car purchase behaviour. But contrary to Ryan et al. (2009), who found that an increase in petrol circulation taxes of 10% could result in a decrease in fleet CO_2 emissions of 0.3 g per km in the short run and 1.4 g in the long run, we find that an increase in the annual road tax level and CO_2 sensitivity increases the CO_2 intensity of new petrol cars. We are not sure what causes this finding. It is not obvious that individuals account for future annual tax expenses, as discussed in Section 6.2. It is possibly because annual road taxes are not salient, but the high collinearity between annual road taxes may also play a role.

We find that higher petrol fuel taxes tend to reduce the fleet's emission intensity, while diesel fuel taxes tend to reduce average emissions for the diesel fleet but also induce substitution of petrol cars for diesel cars. The finding is consistent with Ryan et al. (2009), but a subtle and important distinction from the general conclusion in the literature that higher petrol prices tend to lead to more fuel-efficient cars (Burke and Nishitateno, 2013; Davis and Kilian, 2011; Klier and Linn, 2013).

There is a clear positive potential for fiscal instruments as part of the set of policy measures aimed at reducing CO_2 emissions from cars.[29] Our findings thus support the European Commission's third policy pillar. Yet, we should not overstate the contribution of registration taxes. The overall effect of the registration tax changes that we identify, a 1.3% improvement of fuel efficiency, is small compared to the overall achievement over the period observed (Figure 6.1). Innovation and other policy instruments have played a substantial role. In that context, it is important to understand that various policy instruments can strengthen, but also counter each other. In the European Directive EC/443/2009 car manufacturers are evaluated (from 2015 onwards) based on their average emissions of cars sold across all EU countries. Increased sales of fuel-efficient cars in one country thus allows manufactures to sell

[29] See Burke (2014) for a broader discussion.

more fuel-inefficient cars in other countries. The principle, sometimes referred to as a 'waterbed-effect', implies that environmental gains from fiscal national policies can leak away as the sale of more fuel-efficient cars in a country with a fiscal regime that puts a large premium on CO_2 emissions, is countered by the sale of more fuel-intensive cars in other countries. National fiscal policies, aimed at the demand side, and in line with the third pillar of EU policies, might thus be less effective conditional on the effectiveness of the first pillar of EU-policy, aimed at the supply of fuel-efficient cars throughout the EU. Given an exogenously set ceiling for the EU-wide CO_2 emissions, there is no clear economic gain from a diversified fiscal regime between EU countries, while there are social costs (Hoen and Geilenkirchen, 2006). Indeed, a few years ago, the EU proposed to harmonize vehicle taxes in the EU, but the proposal was rejected by the Member States. We also mention a few other potential disadvantages of fiscal support of fuel-efficient cars.

In this paper, we focus on the average emission intensity of new cars. Reducing taxes for small, fuel-efficient cars can lead to scale effects (i.e. more cars) and intensity-of-use effects (i.e. more kilometres per car). Konishi and Meng (2014) show that in a green tax reform in Japan, this scale effect offset the composition effect (i.e. a bigger share of fuel-efficient cars) by approximately two third. In addition, there is a rebound effect. Fuel-efficient cars are cheaper to drive, and a portion of the CO_2 gains by CO_2-based vehicle purchase tax is lost as the fuel-efficient cars increase car travel demand (Khazzoom, 1980). The existence of the effect is undisputed, but its magnitude remains an issue of debate (see e.g. Binswanger, 2001; Brookes, 2000; Sorrell and Dimitropoulos, 2008). Frondel and Vance (2013) estimated that 44-71% of potential energy savings from efficiency improvements in Germany between 1997 and 2012 were lost due to increased driving. The rebound effect may be mitigated if part of the increase in sales of new, clean cars is due to consumers sooner retiring their less-efficient cars.

Of the policies aimed at reducing CO_2 emissions, excise fuel duties most directly target the environmental objective, specifically since the use of the car is accountable for about 80% of CO_2 emissions in its life-cycle (Gbegbaje-Das, 2013). Fuel excise duties are also closer to the 'polluter pays-principle', one of the leading principles of European Environmental Policy (European Parliament, Council of the European Union , 2004). Taxing fuels would lead to more efficient cars and lower mileage without rebound effects (Chugh and Cropper, 2014), making it the preferred instrument for reducing road transport emissions. Yet significant fuel tax increases are politically costly.

There are also secondary effects of fiscal policies. When consumers choose lighter cars that are more fuel-efficient, not only CO_2 emissions fall but emissions of NO_X

and PM_{10} as well. A weight reduction of 10% results in a decrease of the emission of NO_X with 3-4% (Nijland et al., 2012). On the other hand, substituting diesel cars for petrol cars improves CO_2 fuel efficiency by about 10-20%, yet increases the emissions of NO_X (Nijland et al., 2012). In the case of PM_{10} the situation is not clear, as modern petrol cars with direct injection might emit more PM_{10} than modern diesel cars (Köhler, 2013). Lighter cars also reduce fatalities for drivers of other vehicles, pedestrians, bicyclists, and motorcyclists (Gayer, 2004; White, 2004). The design of the fiscal regime, encouraging lighter cars or encouraging diesel cars, can alter the secondary effects substantially.

We used CO_2 emission data according to the NEDC guidelines. It is known that the tests typically report lower emissions compared to realistic conditions, especially for cars that score very well at the tests (Ligterink and Bos, 2010; Ligterink and Eijk, 2014). Moreover, the gap between test results and realistic estimates for normal use have increased over time; from about 8% in 2001 to 21% in 2011, with a particularly strong increase since 2007 (Mock et al., 2012, 2014). The gap between test values and estimates of realistic use values also affects the estimated emission of air pollutants, particularly the emissions of NO_X from diesel cars (e.g. Hausberger, 2010; Vonk and Verbeek, 2010). To continue the use of test-cycles therefore requires an update of procedures and improvement of their reliability as predictor of real-life use.

Finally, we mention three limitations of our study. We proxy the fiscal treatment of personal vehicles, assuming that taxes change continuously with CO_2 emissions. Yet, there are indications that consumers are more sensitive to discrete price increases, such as tax breaks for cars that meet specific criteria (see e.g. Finkelstein, 2009; Klier and Linn, 2015; Kok, 2013). This study did not explicitly model these elements of tax design. Second, about half of the new sales in Europe are company cars (Copenhagen Copenhagen Economics, 2010). One of the reasons for their widespread use is their beneficial tax treatment (Gutiérrez-i-Puigarnau and van Ommeren, 2011), including implicit subsidies as employees often do not bear the variable costs of private use (Copenhagen Copenhagen Economics, 2010). Therefore, private consumers and business consumers react differently to price signals such as fiscal rules and fuel taxes. We do not have available data on the two separate markets and must leave this topic to future research. Third, we did not consider other fiscal measures such as the scrap subsidies which had major effects on sales in various countries, though the effects on the fuel efficiency is considered limited (Grigolon et al., 2016).

Appendix 6

6.A Loglinear detailed model of Section 6.4.2

We construct the country-car-year variables $LOGCO2_{it} = \ln(CO2_{it})$ and $LOGTAX_{cit} = \ln(1+\tau_{cit})$ from our database, and subsequently construct the country averages (equations (6.8) and (6.9)), denoted by a bar over the variables:

$$\overline{LOGCO2}_{ct} = \frac{\sum_i \delta_{cit} LOGCO2_{it}}{\sum_i \delta_{cit}}, \tag{6.A.1}$$

$$\overline{LOGTAX}_{ct} = \frac{\sum_i \delta_{cit} LOGTAX_{cit}}{\sum_i \delta_{cit}}. \tag{6.A.2}$$

We subsequently calculate the CO_2-sensitivity of the tax (6.10), $LOGCO2TAX_{ct}$, by comparing how much taxes increase when CO_2 emissions increase, on average, and weighted:

$$LOGCO2TAX_{ct} = \frac{\sum_i w_{cit}\left(LOGTAX_{cit} - \overline{LOGTAX}_{ct}\right)}{\sum_i w_{cit}\left(LOGCO2_{cit} - \overline{LOGCO2}_{ct}\right)}, \tag{6.A.3}$$

where weights are given by the deviation from the average CO_2 intensity (6.11):

$$w_{cit} = \left(LOGCO2_{cit} - \overline{LOGCO2}_{ct}\right). \tag{6.A.4}$$

We then construct the (virtual) tax rate $LOGTAX_{ct}$ that would apply to a car with a CO_2-emission profile that is typical for the aggregate of all countries ((6.12) and (6.13)):

$$LO\breve{G}CO2_t = \frac{\sum_{c,i} \delta_{cit} LOGCO2_{it}}{\sum_{c,i} \delta_{cit}}, \tag{6.A.5}$$

$$LOGTAX_{ct} = \overline{LOGTAX}_{ct} + LOGCO2TAX_{ct}\left(LO\breve{G}CO2_t - \overline{LOGCO2}_{ct}\right). \tag{6.A.6}$$

The two constructed variables $LOGTAX_{ct}$ and $LOGCO2TAX_{ct}$, are used as independent variables explaining the average emission intensity of the new car fleet (6.14). Note that the country-average CO_2 intensity constructed in (6.8) or (6.A.1) is not the same variable used in the econometric regression, used as independent variable in Section 6.5 (6.14). The country-average CO_2 intensity in (6.8) or (6.A.1) is measured only for those car types for which we have price and tax data, and its purpose is solely to construct the CO_2 sensitivity of car taxes in (6.10) or (6.A.3). The country-average CO_2 intensity used in Section 6.5 (6.14) is from an independent source, and is based on all car sales in a country-year; it is the independent variable that we explain using the country tax variables constructed in Section 6.4.2.

6.B Linear model

In the main text, we characterized a country's tax system by two coefficients: the average rate, and its CO_2 sensitivity, which is defined as *elasticity* of the tax rate with respect to CO_2 emissions. In this appendix, we take a linear approach. Here, the CO_2 sensitivity is instead defined as the increase in the tax *level* for a given increase in CO_2 emissions (in grams per km). To decompose the tax in these elements, we estimate

$$\tau_{cit} = TAX_{ct} p^{p}_{cit} + CO2TAX_{ct} \left(CO2_{cit} - \breve{CO2}_{t} \right), \tag{6.B.1}$$

where τ_{cit} is the tax paid (in euro's) for vehicle i in country c at time t, p^{p}_{cit} is the tax exclusive purchase price, $CO2_{cit}$ the vehicle CO_2 emission in g/km and $\breve{CO2}_{t}$ the average time t CO_2 emissions in g/km. We then characterize a tax system by TAX_{ct}, which is the average tax *rate* as a percentage of the purchase price, and $CO2TAX_{ct}$ which is the additional tax, in euro's, per g/km additional CO_2 emissions.[30]

Table 6.B.1 presents the summary statistics equivalent to Table 6.1, as the numbers in this table are potentially easier to interpret. Consistent with the results for the logarithmic model, we find that from 2001 to 2010, the average registration taxes have fallen, yet its CO_2 sensitivity has increased, for petrol and diesel cars. For example, for diesel cars, the average registration tax fell from 53 percent in 2001 to 44 percent in 2010. In 2001 however, emitting an additional 10 gCO_2/km would increase the tax by 88 euros on average. In 2010, this has increased to 382 euros. Adjusting the decomposition slightly alters the estimation of the average tax rate. In Table 6.1, the 2001 (2010) diesel registration tax rate is 46 (40) percent, for petrol this is 39 (34) percent; in Table 6.B.1 these rates are approximately 7 percentage points higher.

With this decomposition, we consider the effect of the vehicle registration tax rate, and the CO_2 sensitivity of the tax paid on the average CO_2 intensity of newly purchased vehicles. Results are presented in Tables 6.B.2-6.B.4, where Table 6.B.2 also includes results for the diesel share as a transmission mechanism. Since we now take the level of the additional tax on CO_2 emissions, and the level of the average CO_2 intensity of newly purchased vehicles interpretation is slightly different compared to Tables 6.2 and 6.3. Take for example the first column of Table 6.B.2. Here, a 10 percentage point increase in the vehicle registration tax rate is expected to reduce the CO_2 intensity of diesel cars by 0.8 gCO_2/km. Similarly, the coefficient of -0.032 on $CO2TAX$ registration implies that a 10 euro increase in the effective registration

[30] Note that this simultaneous estimation of TAX_{ct} and $CO2TAX_{ct}$ is not a departure from the decomposition strategy in Section 6.4.2, as the decomposition in the main text is equivalent to estimating $\tau_{cit} = TAX_{ct} + CO2TAX_{ct} \left(CO2_{cit} - \breve{CO2}_{t} \right)$, with all variables as defined in Section 6.4.2.

Table 6.B.1: Summary statistics for constructed tax levels and CO_2 sensitivity for EU15 - linear model

		2001-2010				2001	2010
		Mean	Std. dev.	Min	Max	Mean	Mean
Vehicle registration tax rate	Diesel	0.48	0.45	0.15	2.23	0.53	0.44
	Petrol	0.47	0.45	0.15	2.09	0.46	0.42
Vehicle registration tax rate, CO_2 sensitivity	Diesel	17.4	33.1	-76.67	151.8	8.8	38.2
	Petrol	23.2	39.73	-9.56	189.1	20.5	32.3
Road tax rate	Diesel	0.02	0.01	0	0.06	0.02	0.02
	Petrol	0.01	0.01	0	0.07	0.02	0.01
Road tax rate, CO_2 sensitivity	Diesel	-0.49	2.01	-9.08	7.99	-1.38	0.28
	Petrol	-0.84	2.28	-12.27	5.71	-1.48	-0.02

Tax rates are measured as percentage of the tax exclusive purchase price, CO_2 sensitivity in euro per gCO_2/km.

tax rate on CO_2 emissions for diesel cars, is expected to reduce the average CO_2 intensity of diesel cars by 0.32 gCO_2/km. The sign of coefficients is in line with the logarithmic model, but we lose many significant coefficients, indicating that the logarithmic model provides more precise estimates.

Table 6.B.2: Dependence of new car fleet emissions on taxes, per fuel type - linear model

Dependent variable	CO_2 intensity diesel			CO_2 intensity petrol		
	(1)	(2)	(3)	(4)	(5)	(6)
TAX registration	-7.982	-6.329	-22.51***	2.892	2.620	0.257
CO2TAX registration	-0.032	-0.033	-0.005	-0.072	-0.079*	-0.052
TAX road	102.5		73.20	127.5		207.7
CO2TAX road	-0.095		-0.260	0.553		0.683
Fuel tax rate	-35.50**	-36.71**	-18.71	-5.705	-2.812	0.692
Diesel share			-30.07***			-9.874*
(log) income	36.79**	38.64**	11.67	29.45***	25.92***	21.42**
Convergence	-0.042	-0.045	-0.014	-0.047***	-0.049***	-0.039***
Time FEs	Yes	Yes	Yes	Yes	Yes	Yes
Country FEs	Yes	Yes	Yes	Yes	Yes	Yes
Observations	150	150	150	150	150	150
R-squared within	0.295	0.289	0.472	0.406	0.392	0.437
R-squared	0.909	0.908	0.932	0.974	0.973	0.975

Significance: *** p<0.01, ** p<0.05, * p<0.1. Observations are clustered by country. The R-squared within is calculated for the residuals after both time and country FEs.

Table 6.B.3: Dependence of car emissions on taxes, aggregated over fuels - linear model

Dependent variable	(log) CO_2 intensity overall		
	(1)	(2)	(3)
TAX registration (average)	6.589	7.179	
TAX registration (difference)	9.058*	9.448	14.16**
CO2TAX registration (average)	-0.056**	-0.048	-0.063**
CO2TAX registration (difference)	0.001	0.003	
TAX road (average)	189.1		
TAX road (difference)	367.2***		380.3***
CO2TAX road (average)	0.614		0.158
CO2TAX road (difference)	-0.382		
Fuel tax rate (average)	-14.12**	-22.21**	-11.90*
Fuel tax rate (difference)	4.179	6.953	3.046
(log) income	25.58***	27.51***	22.86***
Convergence	-0.042**	-0.064***	-0.049***
Time FEs	Yes	Yes	Yes
Country FEs	Yes	Yes	Yes
Observations	150	150	150
R-squared within	0.595	0.481	0.645
R-squared	0.976	0.969	0.979
TAX registration (joint)	0.047	0.112	
CO2TAX registration (joint)	0.233	0.170	
TAX road (joint)	0.032		
CO2TAX road (joint)	0.390		
Fuel tax (joint)	0.089	0.033	0.244

Averages are unweighted averages over the two fuel types. Differences are computed as {diesel}-{petrol}. Significance: *** p<0.01, ** p<0.05, * p<0.1. Observations are clustered by country. The R-squared within is calculated for the residuals after both time and country FEs. The bottom 5 rows report the p-values of the joint significance tests.

Table 6.B.4: Dependence of diesel share on taxes - linear model

Dependent variable	Diesel share		
	(1)	(2)	(3)
TAX registration (average)	-0.377***	-0.345**	
TAX registration (difference)	-0.053	-0.138	-0.312***
CO2TAX registration (average)	0.001**	0.001	0.002***
CO2TAX registration (difference)	-0.000	0.000	
TAX road (average)	-0.403		
TAX road (difference)	-11.87***		-13.25***
CO2TAX road (average)	-0.001		-0.003
CO2TAX road (difference)	0.019*		
Fuel tax rate (average)	0.467**	0.709***	0.387**
Fuel tax rate (difference)	-0.299	-0.370	-0.379*
(log) income	-0.628***	-0.799***	-0.567***
Time FEs	Yes	Yes	Yes
Country FEs	Yes	Yes	Yes
Observations	150	150	150
R-squared within	0.587	0.314	0.546
R-squared	0.952	0.921	0.948
TAX registration (joint)	0.027	0.036	
CO2TAX registration (joint)	0.030	0.086	
TAX road (joint)	0.017		
CO2TAX road (joint)	0.076		
Fuel tax (joint)	0.016	0.001	0.049

Averages are unweighted averages over the two fuel types. Differences are computed as {diesel}-{petrol}. Significance: *** p<0.01, ** p<0.05, * p<0.1. Observations are clustered by country. The R-squared within is calculated for the residuals after both time and country FEs. The bottom 5 rows report the p-values of the joint significance tests.

6.C Pooled model

In the main text, we distinguish between taxes paid on diesel and petrol vehicles. This is motivated by a clear difference in the taxes levied across the two fuel types (see Table 6.1 and Tables 6.E.1a and 6.E.1b), as well as the large shift in diesel shares and the fact that it seems to be driven by differences in tax treatment. However, as Table 6.E.2 shows, tax rates paid for diesel and petrol vehicles are strongly correlated, inflating standard errors of the individual regressors. To address this issue, we have estimated a 'pooled' model. For this estimation, the tax variables are no longer constructed for each fuel types, but rather generally, across fuel types. Table 6.C.1 below reproduces Table 6.1 for the pooled setup. The constructed tax levels and CO_2 sensitivities lie approximately in between those for the fuel type-specific ones. Table 6.C.2 then shows our estimation results. Estimations are both qualitatively and quantitatively in line with the results using the averages and differences of the variables (Table 6.3). Note however that the pooled model seems to capture the estimated effect of the average level of either TAX or CO2TAX in Table 6.3. Table 6.3 also shows that for TAX registration and TAX road, the differences across fuel types are relevant, which is an effect the pooled model cannot capture.

Table 6.C.1: Summary statistics for constructed tax levels and CO_2 sensitivity for EU15, pooled

	2001-2010				2001	2010
	Mean	Std. dev.	Min	Max	Mean	Mean
Vehicle registration tax rate	0.34	0.22	0.14	1.04	0.34	0.32
Vehicle registration tax rate, CO_2 sensitivity	0.09	0.13	-0.05	0.5	0.1	0.14
Road tax rate	0.02	0.01	0	0.08	0.02	0.02
Road tax rate, CO_2 sensitivity	-0.004	0.02	-0.09	0.04	-0.01	0.005

Tax rates are measured as percentage of the tax exclusive purchase price, CO_2 sensitivity in euro per gCO_2/km.

Table 6.C.2: Dependence of car emissions and diesel share on taxes, pooled

Dependent variable	CO_2 intensity overall		Diesel share	
	(1)	(2)	(3)	(4)
TAX registration	0.031	0.036	-0.896	-0.821*
CO2TAX registration	-0.102*	-0.088*	0.283	0.245
TAX road	0.610		-0.714	
CO2TAX road	0.611		-2.317	
Fuel tax rate (average)	-0.171**	-0.157*	0.992***	0.936***
Fuel tax rate (difference)	0.108	0.101	-0.632	-0.677
(log) income	0.177***	0.157**	-0.859***	-0.736***
Convergence	-0.051***	-0.052**		
Time FEs	Yes	Yes	Yes	Yes
Country FEs	Yes	Yes	Yes	Yes
Observations	150	150	150	150
R-squared within	0.387	0.359	0.365	0.299
R-squared	0.968	0.966	0.927	0.919

Significance: *** $p<0.01$, ** $p<0.05$, * $p<0.1$. Observations are clustered by country. The R-squared within is calculated for the residuals after both time and country FEs.

6.D Robustness with respect to the economic recession

To further explore whether our results may be driven by the recession, we perform additional sensitivity analysis. The table below presents the full model with all controls (except the transmission mechanisms), where we allow for (1) a quadratic relationship between CO_2 intensity and log income, (2) unemployment to determine CO_2 intensity in addition to log income, and (3) a relationship between CO_2 intensity and the income level (in 1000 euros). The first column reproduces the result from Table 6.3 in the main text. Overall, we find that our results are robust to this alternative specification.

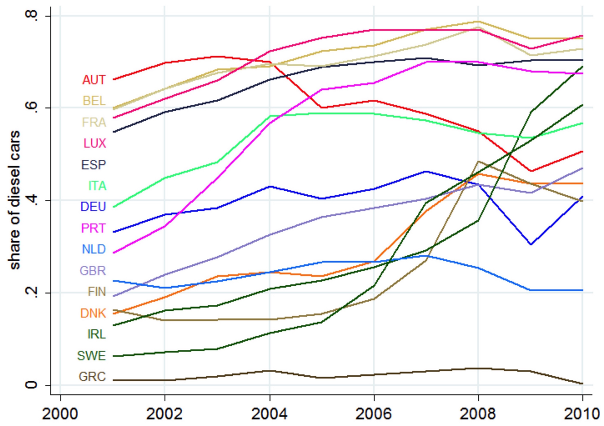
Table 6.D.1: Dependence of new car fleet emissions on taxes, aggregated over fuels - robustness

Dependent variable	(log) CO_2 intensity overall			
	(1)	(2)	(3)	(4)
TAX registration (average)	0.096	0.097	0.097	0.054
TAX registration (difference)	0.192*	0.192*	0.196*	0.185
CO2TAX registration (average)	-0.131	-0.130	-0.134*	-0.139*
CO2TAX registration (difference)	0.003	0.003	0.004	-0.011
TAX road (average)	1.381	1.381	1.381	1.219
TAX road (difference)	1.633*	1.638*	1.646*	1.631*
CO2TAX road (average)	0.854*	0.853*	0.844*	0.703
CO2TAX road (difference)	0.024	0.025	0.016	0.021
Fuel tax rate (average)	-0.121*	-0.121*	-0.128*	-0.090
Fuel tax rate (difference)	0.127*	0.126*	0.134	0.166**
(log) income	0.158***	0.187	0.161***	
(log) income squared		-0.001		
Income				0.003**
Unemployment			0.0004	
Convergence	-0.030	-0.029	-0.029	-0.035
Time FEs	Yes	Yes	Yes	Yes
Country FEs	Yes	Yes	Yes	Yes
Observations	150	150	150	150
R-squared within	0.501	0.501	0.502	0.479
R-squared	0.974	0.974	0.974	0.973
TAX registration (joint)	0.050	0.099	0.019	0.130
CO2TAX registration (joint)	0.000	0.001	0.000	0.000
TAX road (joint)	0.146	0.177	0.153	0.161
CO2TAX road (joint)	0.183	0.185	0.212	0.337
Fuel tax (joint)	0.086	0.112	0.150	0.088

Significance: *** $p<0.01$, ** $p<0.05$, * $p<0.1$. Averages are unweighted averages over the two fuel types. Differences are computed as {diesel}-{petrol}. Observations are clustered by country. The R-squared within is calculated for the residuals after both time and country FEs. The bottom 5 rows report the p-values of the joint significance tests.

6.E Additional figures and tables

Figure 6.E.1: Share of diesel cars in new fleet, by country



Source: Campestrini and Mock (2011)

Table 6.E.1: Constructed tax levels

(a) 2001

	Vehicle registration tax rate		Vehicle registration tax rate, CO_2 sensitivity		Annual tax rate		Annual tax rate, CO_2 sensitivity	
	Diesel	Petrol	Diesel	Petrol	Diesel	Petrol	Diesel	Petrol
Austria	0.31	0.26	0.10	0.10	0.051	0.079	-0.068	-0.087
Belgium	0.20	0.19	-0.03	0.00	0.024	0.015	0.003	-0.002
Denmark	1.12	0.98	0.30	0.43	0.038	0.034	-0.012	0.023
Finland	0.63	0.63	0.03	0.08	0.027	0.040	-0.028	-0.047
France	0.19	0.18	-0.02	0.00	0.000	0.000	0.000	0.000
Germany	0.17	0.15	-0.06	0.00	0.014	0.007	-0.010	-0.005
Greece	0.57	0.33	0.66	0.33	0.009	0.011	-0.019	-0.002
Ireland	0.49	0.44	0.11	0.11	0.025	0.025	-0.001	0.001
Italy	0.21	0.20	-0.07	-0.02	0.014	0.017	-0.008	-0.004
Luxembourg	0.16	0.14	-0.06	0.00	0.004	0.005	-0.003	-0.003
Netherlands	0.47	0.40	0.12	0.13	0.064	0.040	-0.040	-0.009
Portugal	0.47	0.43	0.03	0.23	0.002	0.003	0.002	0.001
Spain	0.25	0.22	-0.03	0.07	0.005	0.005	-0.003	-0.002
Sweden	0.24	0.23	-0.02	0.00	0.036	0.010	-0.016	-0.003
UK	0.20	0.17	-0.11	-0.02	0.020	0.030	-0.027	-0.029

(b) 2010

	Vehicle registration tax rate		Vehicle registration tax rate, CO_2 sensitivity		Annual tax rate		Annual tax rate, CO_2 sensitivity	
	Diesel	Petrol	Diesel	Petrol	Diesel	Petrol	Diesel	Petrol
Austria	0.27	0.24	0.16	0.16	0.025	0.028	0	0.005
Belgium	0.2	0.19	0.02	0.01	0.015	0.015	0.006	0.008
Denmark	1	0.89	0.25	0.53	0.025	0.024	0.010	0.024
Finland	0.46	0.43	0.35	0.23	0.023	0.035	-0.021	-0.030
France	0.19	0.19	0.03	-0.02	0	0	0.001	0
Germany	0.18	0.18	0	0.01	0.019	0.02	-0.004	-0.008
Greece	0.4	0.3	0.16	0.25	0.02	0.013	0.001	0.015
Ireland	0.42	0.39	0.32	0.22	0.014	0.021	0.033	0.043
Italy	0.21	0.22	-0.03	-0.04	0.015	0.015	0.003	0.005
Luxembourg	0.15	0.15	-0.01	-0.01	0.004	0.007	0.008	0.004
Netherlands	0.46	0.38	0.26	0.26	0.068	0.038	-0.021	-0.008
Portugal	0.48	0.35	0.35	0.22	0.01	0.011	0.005	0.001
Spain	0.21	0.22	0.16	0.12	0.005	0.005	0	-0.003
Sweden	0.24	0.24	0.06	0.001	0.017	0.008	0.011	0.001
UK	0.19	0.18	-0.01	-0.05	0.007	0.010	0.012	0.011

Table 6.E.2: Correlation between vehicle fiscal measures

			Registration				Annual				Fuel	
			Petrol		Diesel		Petrol		Diesel		Petrol	Diesel
			Level	CO_2	Level	CO_2	Level	CO_2	Level	CO_2		
Registration	Petrol	Level	1									
		CO_2	-0.38***	1								
	Diesel	Level	**0.67*****	-0.16	1							
		CO_2	-0.21***	**0.61*****	0.24***	1						
Annual	Petrol	Level	0.06	-0.09	0.13	-0.07	1					
		CO_2	-0.06	0.11	-0.13	0.12	**-0.90*****	1				
	Diesel	Level	0.00	-0.09	0.08	-0.11	**0.85*****	**-0.76*****	1			
		CO_2	0.08	0.14*	0.02	0.18**	**-0.76*****	**0.84*****	**-0.76*****	1		
Fuel	Petrol		-0.03	0.09	-0.04	0.01	0.05	-0.04	0.04	-0.11	1	
	Diesel		-0.03	0.10	0.03	0.07	0.14*	-0.04	0.15*	-0.09	**0.75*****	1

Correlations for variables after taking out time and country fixed effects. Significance: *** p<0.01, ** p<0.05, * p<0.1. In bold those >0.5. Annual taxes are multi-collinear.

Supplementary Appendix 6

6.F Subgroup analysis

For all types of taxes, estimated tax rates vary considerably across countries. In addition to this variation, countries also seem to clearly choose what tax instruments (not) to use. Germany for instance, has low or no vehicle registration taxes in addition to the VAT. A question one can ask is whether this affects our results. In this section, we explore whether our results are sensitive to countries that do not employ registration taxes. To do so, we identify a group of five countries that, based on our estimates, do not use registration taxes. We construct a dummy variable I_{noac} which is equal to 1 for these countries, and include interaction terms between this dummy and policy variables in the Table 6.2 and 6.3 regressions in the main text. We establish that our results are robust to the inclusion of such interaction variables, and there is little evidence for sizeable differences in the response to policies between the two groups of countries.[31]

Tables (6.E.1a) and (6.E.1b) list for petrol and diesel, the level and CO_2 sensitivity of the vehicle registration taxes and the annual taxes. Based on these tables, additional inspection of the data for the entire 2001-2010 period, and a comparison with VAT rates, we classify Belgium, Germany, Luxemburg, Sweden and the United Kingdom as the five countries that do not use acquisition taxes for the entire 2001-2010 period.[32]

Table 6.F.1 displays the results for the CO_2 intensity for diesel and petrol cars respectively, now including also the interaction effects. For all policy variables, the size, sign and significance of the coefficients are unaffected by the inclusion of the interaction variables. An exception is the coefficient of the (petrol) CO_2 registration tax in table 6.F.1, column 8. This coefficient turns just insignificant ($p = 0.102$) when the interaction variables are included. The only significant interaction term is the interaction between the road tax rate and I_{noac}, for the diesel regression, column 2; higher road taxes seem to lead to higher diesel CO_2 intensity. For this regression, the interaction terms are also jointly significant (they are not for the other regressions,

[31] We also performed an alternative exercise, where we ran the regressions from the main text on a reduced sample which only included the countries with significant acquisition taxes. Despite a loss in significance of some variables due to the reduced sample size, results are generally in line with the regressions including the interaction terms.

[32] For diesel cars, also France and Italy do not seem to employ acquisition taxes. However, these taxes are significant for petrol cars. We ran additional regression where we add those two countries to the previous five and find that results are robust to this alternative classification. Note that acquisition taxes are also low in Spain. However, comparing diesel rates to the Spanish VAT reveals that some additional taxes were in place. This is also indicated by the CO_2 sensitivity of registration taxes in Spain, which is more positive than for the group of five countries.

see bottom row).

Next we consider the overall effect of car taxes on the new fleet emission intensity, as reported in Table 6.3 in the main text, and including interaction effects in Table 6.F.2. Again, results are generally robust to the inclusion of the interaction terms. The only interaction term that is individually sigificant is the average fuel tax rate in column (6), which suggests that fuel taxes have a more pronounced negative effect on the CO_2 intensity in countries with low registration taxes. The interaction terms are only jointly significant if all are included (column 2).

Table 6.F.1: Dependence of new car fleet emissions on taxes, per fuel type - subgroup analysis

Dependent variable	(log) CO_2 intensity diesel				(log) CO_2 intensity petrol			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
TAX registration	-0.021	0.006	-0.027	-0.039	-0.031	-0.047	-0.028	-0.063
CO2TAX registration	-0.099**	-0.093**	-0.095**	-0.093**	-0.140**	-0.126*	-0.136*	-0.119
TAX road	0.182	-1.374			1.746**	1.614**		
CO2TAX road	0.386	-0.324			1.092**	1.036**		
Fuel tax rate	-0.304***	-0.249**	-0.303***	-0.289**	-0.057	-0.034	0.004	0.03
$I_{noac}\times$TAX registration		0.024		0.173		0.083		0.156
$I_{noac}\times$CO2TAX registration		0.055		-0.035		-0.091		-0.052
$I_{noac}\times$TAX road		4.213**				0.097		
$I_{noac}\times$CO2TAX road		0.701				-0.118		
$I_{noac}\times$Fuel tax rate		-0.048		-0.019		-0.081		-0.113
(log) income	0.251**	0.223*	0.233**	0.235**	0.193***	0.213***	0.150**	0.182***
Convergence	-0.051*	-0.034	-0.048*	-0.049*	-0.028**	-0.032**	-0.030**	-0.038**
Time FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	150	150	150	150	150	150	150	150
R-squared within	0.310	0.366	0.303	0.305	0.347	0.353	0.279	0.293
R-squared	0.915	0.922	0.914	0.915	0.973	0.9574	0.970	0.971
noac (joint)		0.083		0.901		0.959		0.715

Significance: *** $p<0.01$, ** $p<0.05$, * $p<0.1$. Columns 1, 3, 5 and 7 replicate columns 1-4 from Table 6.2, respectively. I_{noac} is a dummy variable that is equal to 1 for Belgium, Germany, Luxemburg, Sweden and the United Kingdom, and equal to 0 for all other countries. Observations are clustered by country. The R-squared within is calculated for the residuals after both time and country FEs. The bottom row report the p-value of the joint significance test of the interaction terms.

Table 6.F.2: Dependence of new car fleet emissions on taxes, aggregated over fuels - subgroup analysis

Dependent variable	(log) CO_2 intensity overall					
	(1)	(2)	(3)	(4)	(5)	(6)
TAX registration (average)	0.096	0.043	0.079	0.058		
TAX registration (difference	0.192*	0.207**	0.148	0.171*	0.202**	0.217**
CO2TAX registration (average)	-0.131	-0.142	-0.104	-0.111	-0.131***	-0.129**
CO2TAX registration (difference)	0.003	0.011	-0.005	-0.005		
TAX road (average)	1.381	0.969				
TAX road (difference)	1.633*	1.630*			1.471**	0.929
CO2TAX road (average)	0.854*	0.838			0.135	0.313
CO2TAX road (difference)	0.024	0.362				
Fuel tax rate (average)	-0.121*	-0.053	-0.149	-0.091	-0.101	-0.014
Fuel tax rate (difference)	0.127*	0.154*	0.106	0.173	0.076	0.145
$I_{noac}\times$TAX registration (average)		-0.23		0.318		
$I_{noac}\times$TAX registration (difference)		-0.567		-0.376		-0.314
$I_{noac}\times$CO2TAX registration (average)		0.052		-0.219		-0.112
$I_{noac}\times$CO2TAX registration (difference)		-0.041		-0.074		
$I_{noac}\times$TAX road (average)		1.529				
$I_{noac}\times$TAX road (difference)		-0.137				1.040
$I_{noac}\times$CO2TAX road (average)		-0.944				-1.319
$I_{noac}\times$CO2TAX road (difference		-0.792				
$I_{noac}\times$Fuel tax rate (average)		-0.238		-0.173		-0.282*
$I_{noac}\times$Fuel tax rate (difference)		0.117		-0.068		0.071
(log) income	0.158***	0.172**	0.148***	0.145**	0.136**	0.178**
Convergence	-0.03	-0.031	-0.049**	-0.052***	-0.033*	-0.038*
Time FEs	Yes	Yes	Yes	Yes	Yes	Yes
Country FEs	Yes	Yes	Yes	Yes	Yes	Yes
Observations	150	150	150	150	150	150
R-squared within	0.501	0.550	0.394	0.425	0.458	0.501
R-squared	0.974	0.976	0.968	0.970	0.971	0.974
noac (joint)		0.017		0.872		0.590

Averages are unweighted averages over the two fuel types. Differences are computed as {diesel}-{petrol}.Significance: *** p<0.01, ** p<0.05, * p<0.1. Columns 1, 3, and 5 replicate columns 1-3 from Table 3. I_{noac} is a dummy variable that is equal to 1 for Belgium, Germany, Luxemburg, Sweden and the United Kingdom, and equal to 0 for all other countries. Observations are clustered by country. The R-squared within is calculated for the residuals after both time and country FEs.

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